# Towards inclusive GIS in the Congo Basin: an exploration of digital map creation and an evaluation of map understanding by non-literate hunter-gatherers

by

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I, Julia Altenbuchner confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

*London,*
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# Abstract

Sustainable and socially just natural resource management is one of the fundamental development challenges humanity is facing today. Communities living in remote areas possess unique insights about their natural resources. While this knowledge is critical to climate change, it is difficult for them to engage in environmental protection. Geographic Information Science (GIS) plays a central role in resource management, as it is utilised in spatial decision making processes. However, the literature argues that its use is too challenging for marginalised communities.

Working with indigenous hunter-gatherers in the Congo Basin without prior exposure to technology or maps, this research moves towards enabling them to become active stakeholders in decision making so that they understand how to capture environmental knowledge and gain power through ownership. (Participatory) GIS, Human Computer Interaction, Action Research and Citizen Science concepts are adapted to the local context to address the lack of mapping of these areas, and the increased understanding of if and how digital, high resolution orthographic maps incorporated in digital mapping tools can be understood by people with no prior exposure to maps and technology.

Different set-ups of low-cost Unmanned Aerial Vehicles and consumer grade cameras were tested and evaluated for suitability to generate high-resolution maps in-situ for previously unmapped and disconnected contexts. Applying a computer log analysis approach to overcome local obstacles, three experiments were carried out to test whether the resulting aerial orthophotos are understood as a representation of familiar geographical landscapes. For each of the experiments, a bespoke app functioning without an internet connection was developed.

The research shows that the majority of the 136 participants could find as well as edit known features on the map and all participating groups were able to utilise a map for a Treasure Hunt game. Additionally, a number of methodological amendments are proposed to allow standardised research methods to be applied in a context where usability experiments are significantly challenged.

This thesis is dedicated to my colleague and friend *Gill Conquest*.

Gill did not have the chance to submit her own thesis but many of the thoughts and insights she has shared with me over the years have made it into this work. Gill was an incredibly talented person with a brilliant mind and a wonderfully loud personality. The way she was fighting against cancer and her positive approach to life until the end was an inspiration and put the struggles accompanied with writing a PhD thesis into perspective. I am most grateful that this project has brought us together and that we got to spend four years in which we shared the struggles and joys of this research.

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# List of Acronyms

**ACD** Activity-Centred Design

**API** Application Programming Interface

**AR** Action Research

**CAR** Central African Republic

**CAA** Civil Aviation Authority

**CIB** Congolaise Industrielle des Bois

**CBM** Community-Based Monitoring

**CHDK** Canon Hack Development Kit

**CMVS** Clustering Views for Multi-View Stereo

**CW** Cognitive Walkthrough

**CSV** Comma Separated Values

**DEM** Digital Elevation Model

**DRC** Democratic Republic of the Congo

**DSM** Digital Surface Model

**ESA** European Space Agency

**EU** European Union

**ExCiteS** Extreme Citizen Science

**EXIF** Exchangeable Image File Format

**FLEGT** Forest Law Enforcement, Governance and Trade

**FOV** Field of View

**FPIC** Free, Prior and Informed Consent

**FSC** Forest Stewardship Council

**GCP** Ground Control Point

**GDP** Gross Domestic Product

**GIS** Geographic Information System

**GISc** Geographic Information Science

**GPS** Global Positioning System

**GSM** Global System for Mobile Communications

**GUI** Graphical User Interface

**GVIS** Geovisualisation

**HCI** Human-Computer Interaction

**HCI4D** Human-Computer Interaction for Development

**HE** Heuristic Evaluation

**HTTP** Hypertext Transfer Protocol

**ICT** Information and Communications Technology

**ICT4D** Information and Communications Technologies for Development

**IGN** Institut Géographique National

**IM-FLEG** Independent Monitoring of Forest Law Enforcement Systems and Governance

**IQR** Interquartile Range

**IxD** Interaction Design

**LDCs** Least Developed Countries

**KML** Keyhole Markup Language

**LOCF** Last Observation Carried Forward

**MDGs** Millennium Development Goals

**MSF** Médecins Sans Frontières

**MVS** Multi-View Stereo

**NASA** National Aeronautics and Space Administration

**NFC** Near-Field Communication

**NGO** Non-Governmental Organisation

**NPFD** Non-Permanent Forest Domain

**ODK** Open Data Kit

**OSM** OpenStreetMap

**PAR** Participatory Action Research

**PDA** Personal Digital Assistant

**PFD** Permanent Forest Domain

**PGIS** Participatory Geographic Information System

**PPGIS** Public Participation GIS

**PMVS** Patch-based Multi-View Stereo

**PNG** Portable Network Graphics

**PAR** Participatory Action Research

**PRA** Participatory Rural Appraisal

**RAM** Random Access Memory

**RANSAC** Random Sample Consensus

**REDD** Reduced Emissions from Deforestation and Forest Degradation

**RGBA** Red, Green, Blue, Alpha

**RoC** Republic of the Congo

**RMSE** Root Mean Square Error

**SfM** Structure from Motion

**SIFT** Scale-Invariant Feature Transform

**TEK** Traditional Ecological Knowledge

**TIN** Triangular Irregular Network

**UAV** Unmanned Aerial Vehicle

**UE** Usability Engineering

**UCD** User-Centred Design

| | |
|---|---|
| **UCL** | University College London |
| **UI** | User Interface |
| **UK** | United Kingdom |
| **UTM** | Universal Transverse Mercator |
| **VGI** | Volunteered Geographic Information |
| **VPA** | Voluntary Partnership Agreement |
| **WCS** | Wildlife Conservation Society |
| **WWF** | World Wildlife Fund |
| **XML** | Extensible Markup Language |

# 1 Introduction

"Cartography, we see, is never merely the drawing of maps: it is the making of worlds."

– Harley, 1990: p.16

Maps are never free of value as they invariably carry power and convey social relations. As such, they have always played a central role as weapons of imperialism to enforce dominance (Wood, 1992). In recent times, maps are increasingly being used to contest control (Wainwright and Bryan, 2009) as well as to protect the environment from overexploitation (Harris and Hazen, 2005). Ideally, maps should be harnessed to transform power relationships into ones that are inclusive, sustainable and guarantee social and environmental justice. However, attempts at environmental justice and conservation often exclude local populations and sometimes result in their forced expulsion. To date, most environmental monitoring in remote and environmentally sensitive ecosystems is carried out by expatriate conservation workers, government employees or scientists, but only exceptionally with the informed participation of local inhabitants. How can we act sustainably and justly in a world where the majority of the most affected people are not able to access or share information?

The objective of this research is to extend the scope and geography of participation in decision making in support of social and environmental justice, by enabling communities to become real stakeholders. This implies that they are both able to capture local environmental knowledge as well as gain power through ownership and understanding of mapping processes. The approach followed in this thesis is to investigate whether mapping in general, and Geographic Information Systems (GIS) in particular, can be an appropriate technology for participatory development work in areas where access to maps and technology is traditionally limited. This is particularly the case in remote regions, such as tropical rainforests, which correlate with low levels of education, literacy and a lack of connectivity. Thus, the focus of this thesis is whether indigenous, non-literate forest communities are able to understand and use maps. For this, it is necessary to investigate how to create digital base maps to support local participation in challenging environments on a small budget.

## 1.1 Scope

This research, at its highest level, aims to contribute to environmental and social justice by giving a voice to indigenous forest inhabitants whose lifestyle is threatened by commercial activities such as logging. It is in the interest of the affected population to preserve the forest health as it provides them with all the resources they require for their subsistence. Engaging indigenous people in collecting, sharing, and analysing spatial data is the direct objective of a project called Intelligent Maps, conducted as part of the interdisciplinary research group Extreme Citizen Science (ExCiteS). It further aims to study the participation of communities in participatory environmental monitoring and mapping activities. The project sets the context for this research and is described in detail in chapter 2.

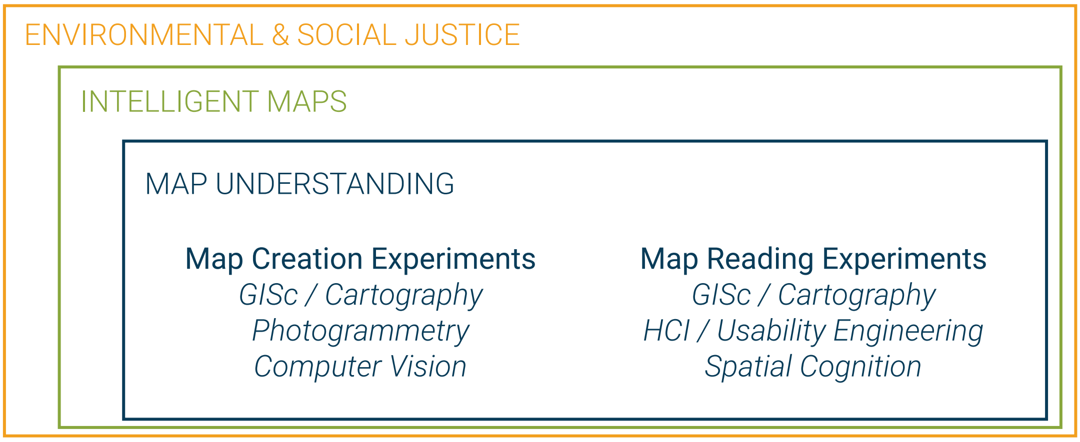



***Figure 1.1*** *Research scope and main disciplines*

The focus of this thesis lies on the topic of map understanding within the context of extending the geography and reach of participatory mapping activities. The research primarily contributes to the field of Geographic Information Science (GISc), but touches on an array of disciplines, with the main ones being listed in figure 1.1. To carry out experiments concerned with map creation, methods from the disciplines of Photogrammetry and Computer Vision are reviewed and applied, with the scope and novelty of this research lying on the application of methods within the constraints imposed by the challenging context. Regarding map understanding experiments, the suitability of using GIS and digital maps for the given context is analysed and evaluated. For this, Usability Engineering protocols are adapted to address language barriers and cultural differences. Literature in spatial cognition is reviewed and taken into consideration to inform the experiment design, however, this research is not primarily concerned with cognitive processes or individual differences in map reading abilities.

## 1.2 Background

This research sets out to contribute to the grand vision of using the potential of maps to transform power relationships into ones that are inclusive, sustainable and guarantee social and environmental justice by evaluating whether maps can be understood by marginalised communities with no mapping culture. It was carried out in a context of the Congo Basin, where the resource base of the forest-dependent population is diminishing. Remote regions are opened up to the commercial activities of logging companies and in the Republic of the Congo local and indigenous communities do not have formally recognised land rights to forest territories.

The Congo rainforest is vast, covering an area of 200 million hectares, giving home to over 150 different hunter-gatherer ethnic groups. Yet, everything under a certain scale on a map inevitably disappears from sight. The most accurate map of the Republic of the Congo is at a scale of 1:200,000 and satellite imagery is limited. The representation of the area as a blur of forest makes it impossible to distinguish between the trees within the forest, let alone spot traces of inhabitants. Trees, in fact, are only of interest inasmuch as they can be commodified. Logging companies operate tree inventories, putting a virtual grid over the forest to define plots and only a tree of a certain constitution and type has a price tag. Beyond that, the forest is unmapped, its indigenous population neglected. As Fox et al. (2005: p.7) put it, "(c)ommunities that do not have maps become disadvantaged as rights and power are increasingly framed in spatial terms".

Increase the scale on a map, however, and trees can start to gain shape. Increase it even further and the outlines of a hut can be made visible and where there is a hut there is human life. Current maps that do not cater for these scales treat people as not present. This research shows that it is possible to increase the scale to make trees distinguishable and people visible. The research goes beyond mere visibility, which aims at acknowledgement of existence. The ultimate goal of being 'seen' as well as 'heard' is typically depicted using the concept of 'voice', which stands for the opportunity to speak, be heard and influence decisions affecting one's life (Couldry, 2010). Transferring digital mapping technologies designed in and for the industrial parts of the world to remote areas, where literacy and formal education are rare, presents numerous challenges. The set goal of this research is to evaluate the understanding of digital maps, which have the potential to be utilised as a means of communication with external stakeholders and thereby give local communities a voice.

This section introduces the concepts of sustainable development and social justice, as well as the paradigms and grass root methodologies relevant to this research, that have emerged in the pursuit of these principles. The final section outlines the contributions and the structure of this thesis.

### 1.2.1 Sustainable Development

Sustainable development is a concept resulting from the awareness that there are global links between environmental problems and socio-economic issues such as poverty, inequality and concerns about the future of humanity (Hopwood et al., 2005). This idea was widely articulated for the first time in the 1987 *Brundtland Report* published by the United Nations. It states that:

> "Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987: p.8).

The innovative message of this report was that truly sustainable progress is possible only if interlinked aspects of economy, environment and social well-being are addressed simultaneously (Johnston and Everard, 2007). Until recent times the environment has been regarded as an infinite supply of resources, external to humanity. It has been used and exploited, with only a few exceptions, such as areas preserved as wilderness areas or parks. Environmental problems were seen at a local scale and the general conception of people's relationship with the environment was as humanity's triumph over nature. Linked with the development of capitalism, the industrial revolution, and modern science, this 'Promethean' view (Dryzek, 2013) was grounded in the belief that human knowledge and technology could overcome all crises (Hopwood et al., 2005). However, in 1972 the book *The Limits to Growth* (Meadows et al., 1972) was published, in which the authors used computer modelling to explore the interaction between exponential growth and finite resources in a range of scenarios. The variables used were world population, industrialisation, pollution, food production and resource depletion. The model predicted "overshoot and collapse" (Meadows et al., 1972: p. 125) before the year 2100 if considerable action was not taken.

At the beginning of the 21st century, humanity has come face-to-face with reality, now recognising that the means used to overcome resource scarcity have contributed to the next generation of environmental problems (Redclift, 2005). Ehrlich and Ehrlich (2013: p.1) report that:

> "(T)oday, for the first time, humanity's global civilization – the worldwide, increasingly interconnected, highly technological society in which we all are to one degree or another, embedded – is threatened with collapse by an array of environmental problems."

The realisation, largely amongst scientists, that humanity is facing a global catastrophe has not been accompanied by popular awareness, or pressure to oppose the political and economic influences driving the current crisis. There is little chance of changing course fast enough without serious pressure from the public demanding action. A central psychological barrier counteracting what Ehrlich and Ehrlich (2013) call 'foresight intelligence', is the distribution of costs and benefits through time: the costs are to be paid in advance, benefiting mainly unknown people and future generations.

The importance of wide public involvement in policy and practice to achieve sustainable development was recognised in the Brundtland report (WCED, 1987: p.63):

> "The law alone cannot enforce the common interest. It principally needs community knowledge and support, which entails greater public participation in the decisions which affect the environment. This is best secured by decentralising the management of resources upon which local communities depend, and giving these communities an effective say over the use of the resources. It will also require promoting citizens' initiatives, empowering people's organisations, and strengthening local democracy"

Sustainable development has a strong commitment to social equity, with a view that access to livelihoods, good health, resources, and economic and political decision making are connected. In the absence of people having control over their lives and resources, inequality and environmental degradation are inevitable (Hopwood et al., 2005). Formal recognition of the importance of community participation and empowerment in creating and implementing the necessary changes are required in a sustainable world. Diane Warburton, editor of the book *Community and Sustainable Development: Participation in the Future*, claims that community-driven environmental action has gained strength and knowledge over the past 20 years and has now reached a level of maturity (Warburton, 2013). This is true both in developed and developing communities, with the latter more likely to be impacted.

### 1.2.2 Social Justice

When in the mid-19th century Jesuit scholar Luigi Taparelli coined the term social justice, it did not receive much attention (Behr, 2003). It was only in the 20th century that the idea re-emerged and in 1919 the International Labour Organisation was formed explicitly placing social justice on its agenda. It did not, however, outline how social justice ought to be achieved (Rodgers et al., 2009). Taken broadly, social justice stands for fairness, mutual obligation and equal opportunity. The concrete implementation of the ideals of social justice is under much debate as to whom it should benefit and in what ways (Rawls, 2009; Cochrane et al., 2016).

Socio-technical barriers stand in the way of equality when it comes to accessing and using technology, resulting in digital inequalities and a digital divide (DiMaggio et al., 2001; Wei, 2012). Groups marginalised by this divide correspond to those who have been socially, politically and economically disfavoured throughout history (Cochrane et al., 2016).

### 1.2.3 ICT4D

The practice of harnessing digital technologies in the service of some of the world's most severe problems has become widely known as Information and Communications Technologies for Development (ICT4D). Despite the lack of formal definition, the practice of ICT4D is centred around the application of Information and Communications Technology (ICT) with the aim of helping poor and marginalised people and communities make a difference to their lives (Unwin, 2009). In the 1990s, the commercialisation of the internet as well as the declaration of the Millennium Development Goals (MDGs) (UN, 2000; UNDP, 2003), which aim to reduce poverty while improving health and education and advancing gender equality, facilitated the emergence of ICT4D. International development organisations and Non-Governmental Organisations (NGOs), who saw potential in deploying ICT solutions to meet the MDGs, became the main drivers in this movement. The first generation, which Heeks (2008) terms ICT4D 1.0 lasted for about a decade, starting in the mid-1990s. It was heavily based on the establishment of rural ICT kiosks – or telecenters – that provide access to ICT for educational, personal, social, and economic development (Rothenberg-Aalami and Pal, 2005). Most of these telecenters failed to survive because the model was too expensive to be sustainable or scalable. These first, often unsuccessful, projects motivated a new search for better-suited solutions – termed ICT4D 2.0. One of the core problems in the first phase was the introduction of inappropriate technologies instead of building on already existing infrastructure. In 2008, less than 0.5% of African villages were connected to internet infrastructure, but half the world's population were mobile phone users – with the fastest growth rates in the poorest regions (Heeks, 2008). Although the diffusion of mobile internet remains a challenge that requires hardware solutions, it is possible to exploit existing call and SMS functionalities. In the past they have been used to remind people with AIDS to take their antiretroviral medicine (Chib et al., 2012), to monitor elections (Adewumi and Daramola, 2010) or to disseminated agricultural information to farmers (Gakuru et al., 2009).

Similar to the Web 2.0 movement (O'Reilly, 2009), ICT4D 2.0 sees the users as active producers and innovators rather than passive consumers. Generally, three modes of innovation can be distinguished: pro-poor, para-poor, and per-poor (Heeks, 2008). Pro-poor innovation, which occurs outside poor communities, often runs into the danger of design-versus-reality gaps through mismatches between assumptions and requirements. Para-poor innovation, where external stakeholders work alongside local communities, have a higher chance of success. However, it must be taken into account that this kind of participation is likely to create divides between designers and communities, such as rich versus poor, computer-expert versus computer-novice, or even urban versus rural. Per-poor innovation occurs within and by poor communities. As new technologies have reached the poor, they have themselves become innovators, by adapting and applying the technology in new ways (Barendregt, 2013).

### 1.2.4 PPGIS, PGIS & VGI

Public Participation GIS (PPGIS) and Participatory Geographic Information System (PGIS) are terms describing processes for capturing and using non-expert spatial information. Although the terms are related, each acronym brings its own contexts, methods, and actors to a collective understanding of PPGIS or PGIS (Sieber, 2006). Tulloch (2008) defines PPGIS as a "a field within geographic information science that focuses on ways the public uses various forms of geospatial technologies to participate in public processes, such as mapping and decision making." The term originates from the United States when in 1996 the National Center for Geographic Information and Analysis (NCGIA) held meetings to discuss how GIS technology can be applied in a variety of ways to support public participation (NCGIA, 1996a; NCGIA, 1996b; Sieber, 2006). At these initial meetings, participants voiced their concerns that applications were overlooking marginalised groups in favour of the privileged, leading to the over-representation of, for example, the U.S. suburbs in comparison to communities lacking even such basics as portable water (Rambaldi et al., 2006). This inequality gave way to a rise in non-traditional PGIS applications, primarily in developing countries (Abbot et al. 1998; Harris and Weiner 1998; Rambaldi and Callosa 2000; Kyem 2001). Whereas the term Public Participation GIS (PPGIS) originates from the developed United States, the term Participatory Geographic Information System (PGIS) emerged from participatory approaches in rural areas of developing countries (Rambaldi et al., 2006) and derives from community integrated GIS (Harris and Weiner 1998) and what Peluso (1995) terms 'counter mapping', mapping to contest the status quo. The term Volunteered Geographic Information (VGI) was coined by Goodchild (2007), describing the creation and dissemination of geographic data provided by volunteers. There is a continuing ambiguity over the use of PPGIS, PGIS, and VGI in the academic literature and in real-world applications (Brown and Kyttä, 2014) as there is no clear line between the terms. In this thesis, the term PGIS will be used, due to its focus on rural areas in developing countries.

PGIS facilitates community participation and improves the collection of data deemed appropriate by participants (Sieber, 2006; Rambaldi et al., 2006). PGIS entails GIS data production alongside collaborative spatial decision making with the central goal of connecting local know-how with classic spatial information (Ahmed et al., 2015). The use of PGIS is typically based on the expectation to boost community involvement in development projects. This requires planning agencies, NGOs and the private sector to establish procedures that facilitate community-based GIS production and use rather than being elitist. In order to do so, PGIS methodologies should be set up and tested in the field, taking into account development concepts and methods from the past that have proven successful. (Abbot et al., 1998; Chambers, 1994; Sieber, 2006). The wide use of GIS in spatial decision making is often regarded with apprehension as it may strengthen elitist development planning due to the high-cost of GIS hardware, software and data, and the fact that GIS needs strong technical expertise (Rambaldi et al., 2006). PGIS is stepping up against this concern by using GIS technology that involves the communities affected by the development projects, thereby acknowledging their needs and capacity (Abbot et al., 1998; Corbett et al., 2006).

### 1.2.5 Citizen Science

In recent years, the engagement of non-professionals in scientific activities has gained a lot of attention under the name of Citizen Science (Bonney et al., 2009; Silvertown, 2009). The realisation that the public can provide free labour, skills (Savage, 2012), computing power (Anderson and Reed, 2009) or even funding (Gerber et al., 2012) has led to a heavy increase in Citizen Science projects. These are usually set in developed countries, targeting educated populations that are familiar with the use of computers or ICT. Simultaneously, decision-makers and NGOs across the world have begun to draw on the abilities of citizen volunteers in order to monitor and manage natural resources and conserve areas at risk. Several cases indicate that Community-Based Monitoring (CBM) efforts are making an impact (Conrad and Hilchey, 2011; Sultana and Abeyasekera, 2008). An important step towards sustainable natural resource management, as well as environmental governance and socio-environmental justice, is to enable local people to share and apply their knowledge more effectively with all stakeholders. Innovative technologies are urgently required to enable scientifically informed sustainable resource management, especially in key places around the world that are critical indicators of global environmental trends and have unique and endangered biodiversity.

ICT has the potential of enabling people to share information, understand their changing environment and act collectively and sustainably. For solutions to be viable in the long term, they must support indigenous communities to more effectively manage vulnerable areas. To date, the extent of participation in Citizen Science projects is often limited to data collection or data processing. Only a small number are co-created, which Roy et al. (2012: p.11) define as "designed by professional scientists and members of the public working together and for which some of the volunteer participants are involved in most or all steps of the scientific process". Similarly, Haklay (2013) proposes a classification framework which has ExCiteS as the highest level of participation, in which citizens act as facilitators as well as experts. Based on this theory, the ExCiteS Research Group at University College London (UCL) is attempting to overcome the limitations of conventional Citizen Science practice by eliminating common barriers to participation. The aim is to enable any community, anywhere, to engage and participate in Citizen Science in a bottom-up manner. The concept of Extreme Citizen Science, building the framework for this research, is further discussed in chapter 2, which provides the context for this research. The remainder of this chapter shows the contributions made by this research and provides an overview of the thesis structure.

## 1.3 Thesis Contributions

This thesis contributes to four main areas of study: mapping unmapped areas, map understanding, map interaction and usability research 'in the wild'. This section provides an initial overview of these contributions, which are further discussed in chapter 8.

1. Mapping Unmapped Areas

This research demonstrates that it is possible to create high resolution maps of areas which are currently insufficiently mapped to support increased participation in local decision making by indigenous communities, and that this can be done on site using relatively low-cost equipment. Specifically:

- UAV-borne aerial mapping techniques can produce high resolution, georeferenced aerial maps of the Congo rainforest, which exceed the quality of all available products.

- Trials of alternate cameras show that a wide-angle action camera is most suitable for this task. The fish-eye lens is of advantage due to its wide angle and the resulting image overlap.

- The required UAV, camera and software can be purchased 'off the shelf' – no customisation is required. Thus, the systematic process proposed in this research can presumably be used by non-experts to transfer mapping techniques to similar challenging environments with restrictions on internet access, processing power, funding, time as well as existing geographic data.

- Equipment to produce high resolution maps is likely to be affordable by non-profit organisations, at a total cost of less than £4500.
- Challenges to be overcome relate both to access to a suitable power supply for the laptop and to legal and other related issues involved with obtaining permits to fly UAVs.

2. Map Understanding

This research demonstrates that indigenous, non-literate people can understand aerial maps of their environment, without prior training. Specifically:

- The maps created by the UAV mapping process developed in this thesis are sufficient for the purpose of mapping the forest environment in the Congo to a level of detail where the indigenous inhabitants on the map can locate individual features of importance to them – e.g. trees, food supplies.
- Map alignment (e.g. with environment or to the North) is not required for reading aerial photographic maps of familiar space.
- Indigenous, non-literate people can understand the meaning of a thematic location marker overlaid on a reference map.
- There is an educational bias with better results being achieved with higher levels of education. This bias also shows in gender difference due to unequal education levels across genders. Age shows no influence on map reading skills.

3. Map Interaction

This research demonstrates that despite not being familiar with modern devices such as tablets, indigenous non-literate people can interact with digital maps on these devices. Specifically:

- Indigenous non-literate people can pan/zoom to navigate to locations marked with an abstract symbol.
- A brief demonstration proved to be sufficient for people to be able to successfully operate pan/zoom functions in an unsupervised scenario.
- Indigenous, non-literate people can update and correct map marker locations and features on a digital map.

4. Usability Research 'In the Wild'

This research demonstrates that a number of existing techniques from usability engineering – in particular activity logging and participant observation – can be transferred from the lab to enable research with non-literate, indigenous communities, overcoming cultural and linguistic barriers. Specifically:

- With appropriate local assistance including on-site translators and using a Free, Prior and Informed Consent (FPIC) approach, it is possible to recruit sufficient participants to be able to draw preliminary conclusions about the effectiveness of computer logging techniques.
- People are often hesitant and overly careful when interacting with a digital touch screen while they are directly observed.
- Interaction logging methods proved sufficient to analyse map usability through the measure of error rates across language and cultural barriers.
- Interaction logging methods paired with GPS location readings proved sufficient to analyse map use behaviour across language barriers in an unsupervised wayfinding exercise, enabling a new method to be developed to analyse this type of data.
- Within the groups studied, there is a collective approach to problem solving.

Digital technologies in development projects have been both praised and criticised by academics and practitioners but have equally been recognised to have the capacity to make a difference (Gaventa and Cornwall, 2008; Tacchi, 2012). Without neglecting the complexities and pitfalls intertwined with such projects, this work suggests that participatory approaches and technology can be introduced and deployed in a way that they have the potential to empower marginalised communities.

While it is unlikely that, in the near future, indigenous communities will be able to run projects completely independent from intermediaries such as NGOs, the introduction of appropriate mapping technologies has the power to decrease direct barriers to active involvement, such as the communication of spatial knowledge. As illustrated by a logging company's willingness to collaborate, efficient and cost-effective workflows can also reduce indirect barriers like reluctance of stakeholder cooperation, thus creating long-term potential for increasing interests in social and environmental justice.

## 1.4 Thesis Structure

The remainder of this thesis is made up of the following chapters:

**Chapter 2: Context & Research Questions**
This chapter provides the context for conducting research on the potential of mapping and data visualisation tools for marginalised, non-literate communities. It starts with a description of the Extreme Citizen Science framework before the social and political environment of the research area is introduced followed by the challenges that need addressing in order to carry out digital mapping experiments with Mbendjele hunter-gatherer communities. An overview of the Intelligent Maps project is given, including its vision, the progress made and how this research fits into the bigger picture. A critical review of previous literature in regard to the Intelligent Maps objective together with the lessons learned from an initial field trip are presented. Finally, the Research Questions of this theses are introduced.

**Chapter 3: Related Work in Geographic Information Science**
This chapter provides an overview of existing literature on map understanding. Cognitive map reading studies are reviewed as well as influences of visual realism, vantage point, perspective and map alignment. The challenges of using interactive mapping environments are discussed before common methods of map creation are presented to support participatory mapping activities and studies in regions that are lacking detailed cartographic visualisations.

**Chapter 4: Related Work in Human-Computer Interaction and Action Research**
This chapter reviews the concepts and methods used in the field of Human-Computer Interaction and Action Research, which underpin the suitability evaluations of digital mapping tools for non-literate users. User-centered design, the principles of usability as well as usability engineering are outlined as well as the concepts and deployment of Action Research.

**Chapter 5: Methodology**
This chapter introduces the general methodology of conducting field experiments with indigenous hunter-gatherer groups in the Republic of the Congo to address the Research Questions outlined in the previous chapter. An overview of the collaborations with local stakeholders is given and the two field visits undertaken to address the research objectives are outlined along with the field experiment and evaluation methodologies and their progression over time.

**Chapter 6: Maps from Aerial Imagery**
This chapter addresses the first Research Question and evaluates the feasibility of map

generation from aerial imagery, when dealing with restrictions imposed by the nature of this project. Technical equipment choices are discussed as well as the implementation of various testing set-ups for the project. The testing scenarios and results are demonstrated before a suitable set-up and processing pipeline for generating maps for the given context is proposed.

**Chapter 7: Map Understanding**
This chapter addresses the second Research Question. Three experiments and methodologies are presented and discussed, each of them aiming to test whether digital true colour orthophotos can be naturally interpreted by hunter-gatherers in the Congo Basin. The three bespoke apps developed for the experiments are described.

**Chapter 8: Discussion**
This chapter summarises the findings and contributions of this PhD in aerial map creation and digital map understanding. Modifications for adapting research protocols to the rainforest are discussed. The constraints imposed by institutional collaboration in given context are highlighted as well as the challenges and opportunities encountered when working in an interdisciplinary setting.

# 2 Context & Research Questions

This chapter provides context for the research addressed in this thesis and specifically outlines the objectives and work carried out by the Extreme Citizen Science (ExCiteS) research group for the 'Intelligent Maps' project. Intelligent Maps, which seeks to empower marginalised populations through participatory mapping activities, is based on earlier work initiated by Dr. Jerome Lewis[1] in collaboration with local populations in the Congo Basin. While communities living in the Congo Basin have varying lifestyles, including semi-nomadic hunter-gatherers as well as sedentary farmers, they all depend on the forest and its resources to various degrees. Despite this dependency, local people are rarely involved in the management of the areas in which they live, and often get forcefully excluded from their lands (West et al., 2006). At the same time, industrial resource extraction is promoted by timber producing countries, and logging roads increasingly open up remote regions of the forest to commercial activities. To counteract this development, work carried out by the ExCiteS research group aims to enable local communities to play an active role in monitoring logging activities in order to demonstrate their claims to forest land. For this, the research group is applying the concepts of Extreme Citizen Science to develop monitoring and analysis tools that are accessible and comprehensible by local populations as well as the scientific community.

The following sections describe the concept of Extreme Citizen Science and introduce the social context of this research with its specific challenges. Next, an overview of the Intelligent Maps project is given, including its vision, progress and how participatory mapping and data visualisation fit into the bigger picture. Data collection tools, developed and deployed as part of this project, are introduced to provide context for the present research. The theoretical gaps, along with the lessons learned from an initial field trip and early prototype testing inform the research questions, which are outlined at the end of this chapter.

[1] Dr. Jerome Lewis is co-director of the Extreme Citizen Science (ExCiteS) research group. As an Anthropologist he has worked with forest people in the Congo Basin since 1993.

## 2.1 Extreme Citizen Science

Recent research has demonstrated that participants in citizen science projects are providing significant contributions to address societal and environmental challenges such as climate change or loss of biodiversity (Silvertown, 2009). Citizen science also has the potential to extend democracy and collaborative decision making (Silva, 2013). The field is further expected to grow, especially given the increasing interest in knowledge co-production by both researchers as well as policy makers (Jasanoff, 2004; Burgess, 2014).

Despite projects with citizen involvement proving successful on many levels, there remains the challenge of participation inequality (Haklay, 2013). Contributors to citizen science projects typically have a high level of formal education compared to the general public. Figure 2.1 represents the educational attainment of participants in three citizen science projects, with numbers extracted from the publications: Galaxy Zoo (Raddick et al., 2013), OpenStreetMap (Budhathoki and Haythornthwaite, 2012) and Transcribe Bentham (Causer and Wallace, 2012). The level of formal education of participants lies significantly above the average in all three projects as over 60% of each project's participants were degree holders. In comparison, only 26.7% of the EU population (28 member states) and 37.6% of the UK population, aged between 15 and 64 years completed an attainment level of tertiary education, equivalent to short-cycle tertiary education, Bachelor's, Master's or PhD level (EuroStat, 2015).

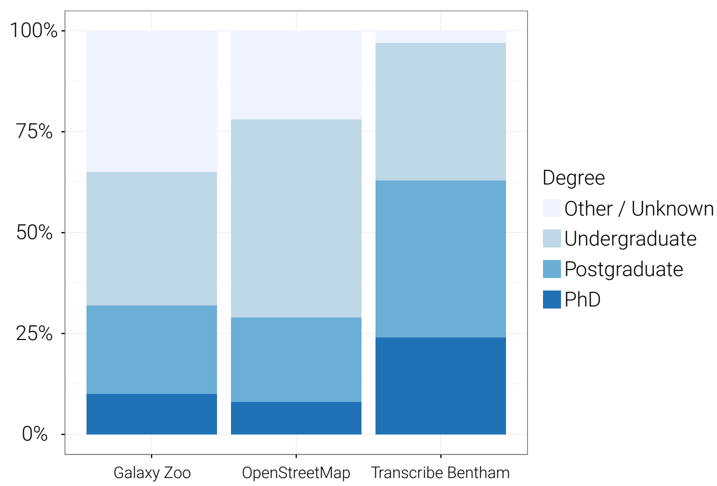



***Figure 2.1*** *Highest degree of participants in citizen science projects*

A further limitation of many citizen science project designs is the scope of citizen involvement. Frequently, participants are regarded as 'sensors' (Goodchild, 2007) or 'data collectors' (Silvertown, 2009). Projects are only rarely set up in a way that includes citizens in the stage of problem definition or in the analysis and interpretation of the data which they collected. Moreover, their contributions are often regarded as not worthy of being used in 'serious research' if the citizen does not have a formal education in science (Hunter et al., 2013).

This research follows an Extreme Citizen Science approach, which aims to overcome traditional boundaries of citizen science projects (Haklay, 2013). This means that projects must be inclusive, regardless of the participants' educational background or literacy level and involvement opportunities must be extended to all project stages from project definition to action (figure 2.2). Extreme Citizen Science is defined as a "situated, bottom-up practice that takes into account local needs, practices and culture and works with broad networks of people to design and build new devices and knowledge creation processes that can transform the world" (ExCiteS group, 2017).

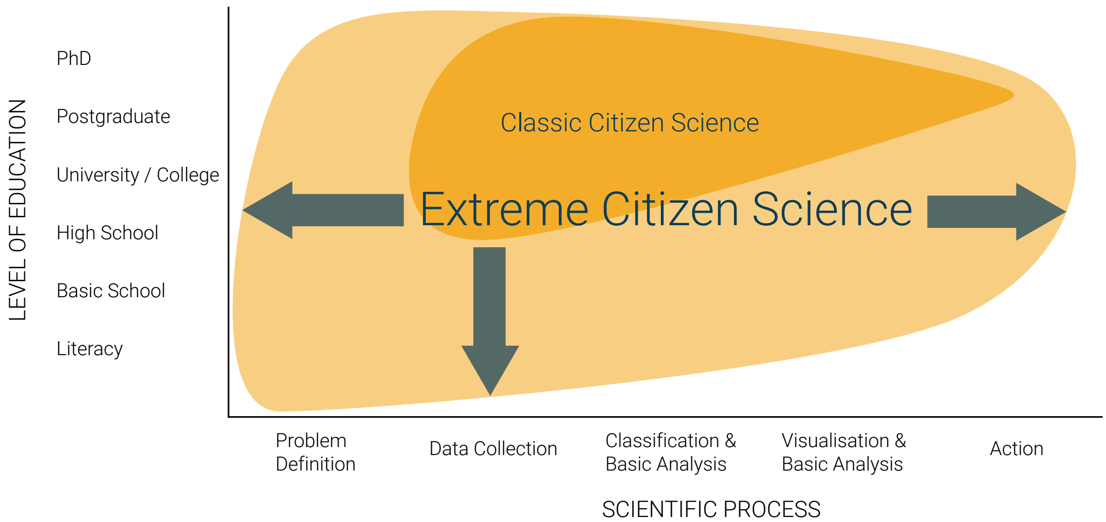



***Figure 2.2*** *Boundaries of classic and Extreme Citizen Science (Haklay, 2013)*

The core framework of Extreme Citizen Science can be used by anyone, reaching from urban communities in the western world to communities of indigenous peoples in tropical rain forests. For this, tools and methodologies need to be adapted to local cultural and environmental conditions. The empowerment of participants to improve their well-being through actions based on their own analyses requires the design of methodologies and tools to be embedded in social and cultural networks.

## 2.2 Social Context – Republic of the Congo

This research is situated in the Republic of the Congo (RoC) as this is a core focus of work by ExCiteS deputy director, Dr. Jerome Lewis. The Congo rainforest covers an area of 200 million hectares located within six African countries. It stretches into Democratic Republic of the Congo (DRC), Republic of the Congo, Cameroon, Central African Republic (CAR), Gabon and Equatorial Guinea, making it the second largest tropical forest after the Amazon rainforest. Much like the Amazon, it is a unique biodiversity centre (Zhou et al., 2014) home to over 10,000 species of plants, 1,000 species of birds, 400 species of mammals and 400 species of fish (UNESCO, 2010). Among the forest's inhabitants are rare animals facing extinction such as the mountain gorilla and the central chimpanzee (Seyler et al., 2010).


***Figure 2.3*** *The Congo Basin (base layer: ESRI)*

The rainforest is also of great significance to people, as it provides food, fuel, fibre and a wide range of other ecosystem services to a total of 200 million people (Norris et al., 2010). Furthermore, it is home to roughly 29 million rural people, up to 500,000 of whom rely heavily on forest resources for their livelihoods (Lewis and Nelson, 2006). As Eisen et al. (2014) note, however, population estimates vary widely. Within the people who live in the forest and rely on it for livelihood to various degrees, two main groups can be differentiated. One is the indigenous or forest people living as hunter-gatherers, and the other is the settled Bantu and Ubangian farmers and fisher people, who are most commonly referred to as Bantu (Conquest, 2014; Eisen et al., 2014).

### 2.2.1 Indigenous People

The indigenous people of the Congo rainforest are collectively referred to as Pygmies and constitute more than 150 different hunter-gatherer ethnic groups (Eisen et al., 2014). This is the largest and most diverse population of nomadic, hunter-gatherers that exists in the world today (Hewlett, 2014). These ethnic groups are often marginalised and face discrimination therefore the word 'Pygmy' has come to have negative connotations. In fact, the usage of the term is forbidden by law in the Republic of the Congo (Law no.5 Article 1, 2011), thus the government and local NGOs are using the French word 'autochtone', meaning 'indigenous' instead (Conquest, 2014). In academic writing, however, the term 'Pygmy' is widely used to describe physically, geographically and culturally different, indigenous peoples in equatorial Africa that share cultural and economic practices, the most common of which is hunting and gathering and the nomadic lifestyle (Lewis, 2002). This thesis uses the term 'Pygmy' in accordance with the academic practice and has no intent to disrespect or offend in any way.

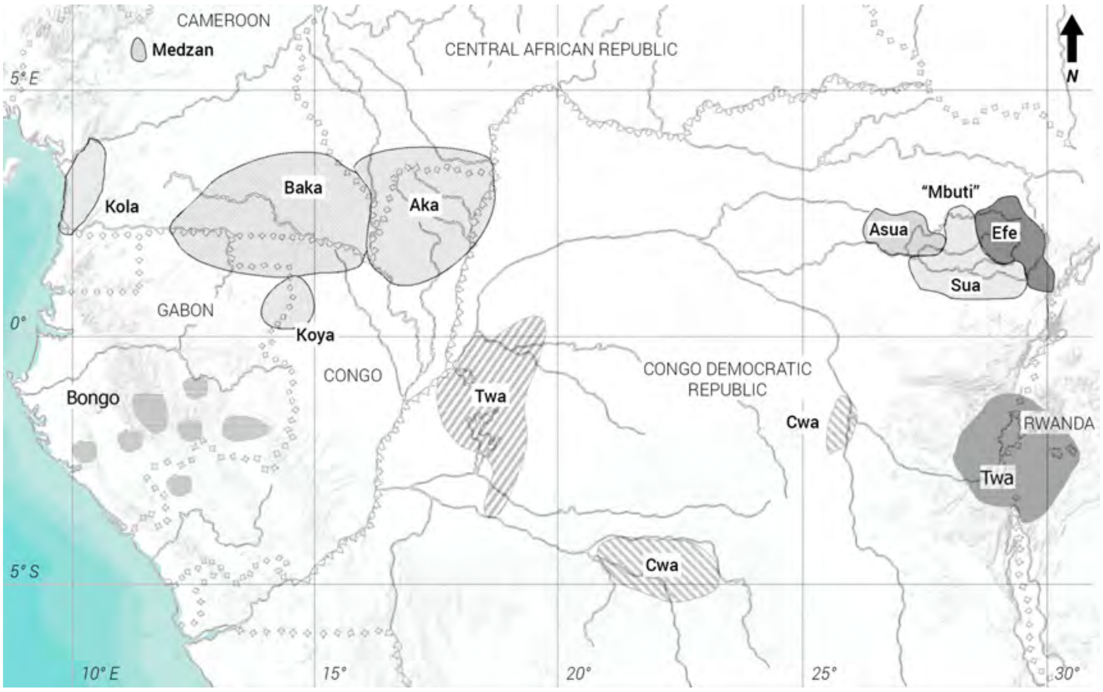



***Figure 2.4*** *Map of prominent Pygmy groups after Bahuchet (2006) base layer ESRI*

Bahuchet (2012) distinguishes between 20 major groups of Pygmies based on ethnic, linguistic and geographical differences. Figure 2.4 highlights the geographical location of the more prominent groups in the Congo rainforest: Aka, Baka, Bongo, Cwa, Koya, Mbuti, Medzan and Twa. Each group is also known under several different names. The case study sites for this thesis lie between the Congo and the Sangha River, primarily inhabited by Aka Pygmies. According to Bahuchet (2012), the Aka group is referred to as Bayaka, Biaka, Babinga, Bambenga, BaMbenzele, Babenzele. In this thesis they are called Mbendjele, according to the naming convention of local project partners.

Despite the ethnic, linguistic and geographical differences, the lifestyles of these communities are similar in that they are closely tied to the forest they inhabit, so much so that they identify themselves as 'forest people' to underline the significance of the forest to their culture, history and livelihood (Lewis, 2001). According to Lewis (2002: p. 54), the Yaka Mbendjele pygmies have a proverb which translates to 'A Yaka loves the forest as he loves his own body.' To them, a life is unimaginable without the forest, which is not only important for its physical resources but also for its cultural and spiritual role in a Pygmy's everyday life. The forest is regarded as a sacred place home to forest spirits and the Pygmies are closely connected to them as 'children of the forest' (Ohenjo et al., 2006). There are over 20 forest spirits and spirit performances described by Lewis (Lewis, 2002). One of the most important spirits of the forest is Djengi (also Ejengi). This is one of the few words that multiple Pygmy languages share.

Most of the Pygmy communities live a nomadic or semi-nomadic existence in small, egalitarian groups that set up temporary huts in different areas of the forest (Ohenjo et al., 2006; Ichikawa, 2014). They sustain themselves by hunting wild animals and gathering wild produce, including fish, reptiles, caterpillars, honey and fruits (Lewis, 2002; Encyclopedia of World Cultures, 2016). The forest is also their source of medicine and a series of materials used for constructing tools, haunting weapons, household utensils etc. (Ichikawa, 2014). Resources acquired from the forest are consumed by the community or offered to nearby settlements in exchange for cultivated products such as manioc, maize and iron. The development of strong trading relationships between certain forest and settled communities have led to complex economic and social dependencies (Encyclopedia of World Cultures, 2016).

### 2.2.2 Settled People

The Bantu and Ubangian farming and fishing communities, collectively referred to as Bantu, migrated to the Congo Basin approximately 3,500 years ago (Eisen et al., 2014) They live in open spaces next to the rainforest and sustain themselves from farming cassava, coco, yams, oil palm, cocoa and coffee and from fishing, trapping and trading (Eisen et al., 2014; Lewis, 2002). Having lived side by side for thousands of years, the indigenous and the Bantu people have developed strong economic and trading relationships (Encyclopedia of World Cultures, 2016). Forest resources such as bush meat, palm-nuts, honey and leaves are traded for items not available in the forest such as iron and salt. Many Pygmies also acquire work in agriculture, clearing farmlands or harvesting land for Bantu communities (Lewis, 2002). Despite these ties, forest people are subject to discrimination from the Bantus who claim exclusive rights over the territories that Pygmies use, as well as over the persons and labour of forest people (Lewis, 2002).

### 2.2.3 Local Issues

Although the lifestyles outlined above are considerably different, both Pygmy and Bantu communities rely on the forest for their livelihoods. Yet, they do not have control of the forest they so much depend on. They are excluded from the management of the areas. Efforts from conservation and natural resource management organisations such as Wildlife Conservation Society (WCS), the World Wildlife Fund (WWF) or other NGOs have even disenfranchised the locals (Ichikawa, 2014). Whereas there has been an aggressive push for industrial resource extraction in parts of Central Africa, the tendency since the 1990s has been to establish protected areas in the rainforest, which have led to the exclusion of indigenous people living on the area (Brockington et al., 2006; West et al., 2006; Lewis, 2008).

The Congo Basin acts as a vital climate regulator and is recognised internationally for its direct impact on climate change. Nevertheless, the forestry and resource extraction sectors have seen a rapid growth in the past two decades (Lewis, 2012). This has lead the Congo Basin's countries to reshape their national legal systems in order to encourage international investments to control and manage forest territories as Cameroon has done in 1994, RoC in 2000, Gabon in 2001 and DRC in 2002 (Lewis, 2012). These measures are taken without considering the needs of the local forest people. Figure 2.5 illustrates the issue of forest dwelling communities not holding any formal usage rights in most of the Congo Basin's countries. Current politics divide the forest into Permanent Forest Domains (PFDs) and Non-Permanent Forest Domains (nPFDs). PFDs are either leased as logging or mining concessions or protected as national parks that prohibit even subsistence hunting for local forest people. The remaining nPFDs do not fit into the above categories and are mostly used by settled communities, putting indigenous forest people in a vulnerable position (Eisen et al., 2014; Lewis, 2012).

Permanent Forest Domains are further divided into multiple concessions called FMUs (Forest Management Units) or UFAs (Unitie Forestieres d'Amenagement). These units are forest plots designated for management, protection, conservation, restoration and production (World Resources Institute (WRI), 2014). According to Lewis (2014), the aim of this division was to attract foreign investment. It brought on a surge of activities from companies interested in exploiting forest resources. During the late 1970s, concessions with river access were mostly of interest, as logging roads had not yet been established due to the lack of efficient machinery. Tractors transported the timber down to the riverbank, where it was then floated down to the sea. During the late 1990s and early 2000s, further concessions became available as a result of advances in technology both in terms of hardware (GPS receivers, earth moving and road making gear) and software (GIS, forestry specific programs relating to road planning, felling, and transformation procedures). This saw a burst of logging activity in the region as the forest became commercially viable (Lewis, 2014).

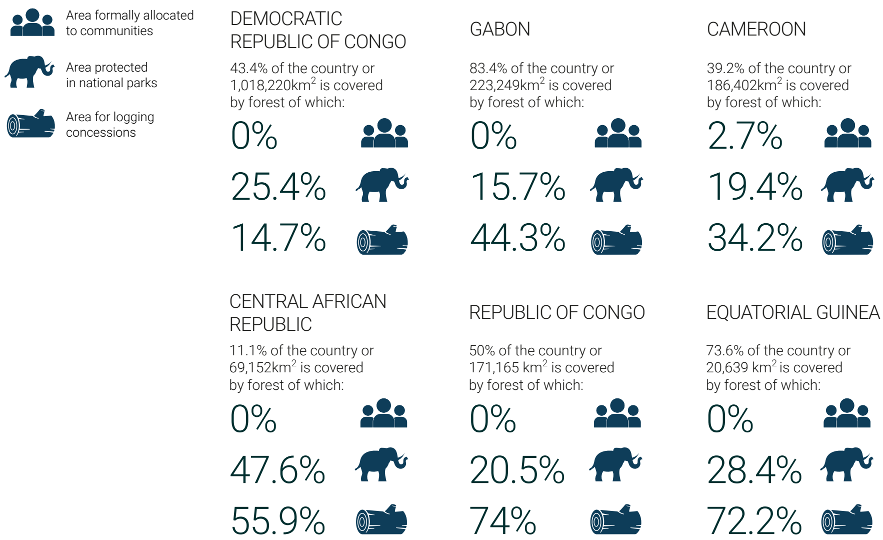



***Figure 2.5*** *Forest ownership and usage rights in the Congo Basin (RFUK, 2012)*

The forest-dependent population of the Congo Basin is experiencing rapid environmental changes. Climate change has become an unpredictable addition to political instability, predatory market forces and rapidly expanding industrial activities (Eisen et al., 2014). The resource base of forest people is diminishing as remote regions are opened up to the commercial activities of logging companies. There are various obstacles that need to be overcome in order to address the needs of local people, such as the weak or non-existent infrastructure, corrupt governments and resource-fuelled conflicts as well as economies dominated by multinationals. These companies extract oil, minerals and timber, and increasingly promote large scale land-use change by establishing palm oil plantations (Lewis and Nelson, 2006).

## 2.2.4 Opportunities

In the Republic of the Congo, local and indigenous communities do not have formally recognised land rights to the forest territories they inhabit. In fact, RoC is one of only ten countries in the world where the government does not administer and reserve forests for such communities (Humphreys, 2006). Despite the lack of formal land rights, local people's way of life is theoretically protected as a result of an array of certification schemes in place in the Congo Basin. These schemes give an incentive to logging companies to harvest and manage forests sustainably in the tropics, while also taking the lifestyle of local people into consideration.

The Forest Stewardship Council (FSC) is the largest certifier in the region and the most popular in Central Africa (UNECE/FAO, 2016). It is an international membership association established in 1993 with members from environmental and social non-governmental organisations, the timber trade, forestry organisations, indigenous people's organisations, community forestry groups, retailers and manufacturers, forest certification organisations, as well as individual forest owners and interested parties (FSC, 2016). The FSC promotes responsible forest management that is environmentally appropriate, socially beneficial and economically viable. Certifying bodies carry out regular forest inspections and audits for the FSC. Although inspectors and auditors are expected to be independent, their services are often paid for by the logging companies they are auditing (Lewis and Nelson, 2006). Logging companies who are FSC certified are able to sell timber in Europe for up to 30% more per cubic metre than companies without FSC certification. As companies operating in landlocked parts of the Congo Basin require a very high oil expenditure in order to power timber transport, they welcome this extra profit (Lewis and Nelson, 2006). According to Cerutti et al. (2014), people living in FSC certified logging concessions are experiencing better social conditions in the Congo Basin than people outside these areas.

An important part of forestry legislation is undergoing revision in the Republic of the Congo after, in May 2010, the country signed a Voluntary Partnership Agreement (VPA) with the European Union (EU). The agreement concerns the Forest Code which outlines the framework for governing the forest sector in the country (WRI, 2014). The VPA was established under the EU's Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan (EC-EDA-ESA-CSG, 2010) with the aim of introducing more participatory forms of forest governance. Under participatory activities, the action plan defines monitoring logging company compliance with socio-economic indicators, mapping readiness for Reduced Emissions from Deforestation and Forest Degradation (REDD), and collecting evidence of both illegal poaching and the negative impacts of anti-poaching enforcement measures on local people. In order for a company to trade with the EU, the country where their logging operations are based will be required to reach a formal agreement with the EU to assure that they are legally exporting timber from the country. An additional incentive to acquire certification by the FSC, whose whose criteria are stricter than those in the VPA, is its formal recognition as proof of legal compliance.

Despite their potential readiness to honour the FSC's requirements for inclusivity, logging companies are often at a loss when it comes to addressing social responsibility as part of certification. Lewis (2014) reports that even companies who have been present in the region for over three decades have little knowledge of the needs of the local indigenous people. The reasons are manifold. Firstly, being semi-nomadic hunter-gatherers, these communities are regularly on the move and physically difficult to track down in remote parts of the forest, especially since there are multiple groups associated with a particular territory. Camps consist of twelve to sixty individuals relocating frequently within the forest as part of regular seasonal movements or for various other reasons such as a simple visit to friends (Lewis, 2014). There is also a linguistic barrier standing in the way of the companies' abilities to understand the needs of the forest people, who speak a multitude of different languages. Even with an interpreter at hand, a cultural obstacle emerges. Being an egalitarian society, the hunter-gatherers have trouble understanding hierarchically organised institutions who expect to find a non-existent leader amongst them. To respect their way of life, the companies would need to communicate with each community as a group, as opposed to the temptation of imposing a 'leader' (Lewis, 2014). Communicating with indigenous people has therefore proven to be both challenging and time-consuming for logging companies.

## 2.3 Context Specific Challenges

The previous section demonstrated how the traditional way of life of forest communities in the Congo Basin is threatened by external economic interests. Based on their nomadic hunter-gatherer lifestyle, a particular characteristic shared by Pygmy groups are their vast knowledge of the forest and the threats it is facing. However, the lack of written information exchange makes it difficult to communicate their needs to outsiders. Nonetheless, local communities have shown willingness to challenge existing power relationships by participating in community mapping projects with the aim to prove their existence and to demand rights over forest usage (Lewis and Nelson, 2006).

According to Gartner et al. (2007: p.247), "(m)aps can now be created and used by any individual with modest computing skills, from virtually any location on the Earth's surface, and for almost any purpose". The following section highlights why even ten years after that statement was published, there are still substantial obstacles to overcome until this statement becomes reality.

### 2.3.1 The Digital Divide

The shift from paper to online digital maps is accompanied by the assumption that internet access is omnipresent. Most people born after 1980 in the western world live as 'digital natives' (Palfrey and Gasser, 2013) in increasingly smart cities, accessing services through cloud subscriptions (Espadas et al., 2008) in an era of ubiquitous computing (Krumm, 2009) and the internet of things (Gubbi et al., 2013). The information age and its rapid advancements of ICT have changed ways of learning, communication, business and health treatment all around the globe (World Bank Group, 2015). Many citizen science projects harness these technologies to reach out to people and share information. The widespread use of mobile internet allows people to share observations in situ and in real time. In citizen science, there is often an implicit expectation that internet access has become truly ubiquitous and that everybody is constantly online (Craglia et al., 2012). This model, however, does not (yet) scale to the rest of the world. Figure 2.6 shows that almost one in two people (47%) worldwide use the internet. The number decreases to one in seven people (15.2%) when regarding the Least Developed Countries (LDCs). The International Telecommunication Union (ITU) (2016) further conclude that by the end of 2016, 53% of the world's population (3.9 billion people) will not use the internet at all, with 75% of these living on the African continent (figure 2.6). Internet users are defined as individuals that have used the internet in the previous 12 months through any kind of device, such as a computer, mobile phone, games machine or digital TV. Access can be via a fixed or mobile network. Figure 2.7 represents the percentage of internet users per country. Assuming that everybody has access to the internet, and producing applications that require participants to be online, automatically excludes a substantial part of people.

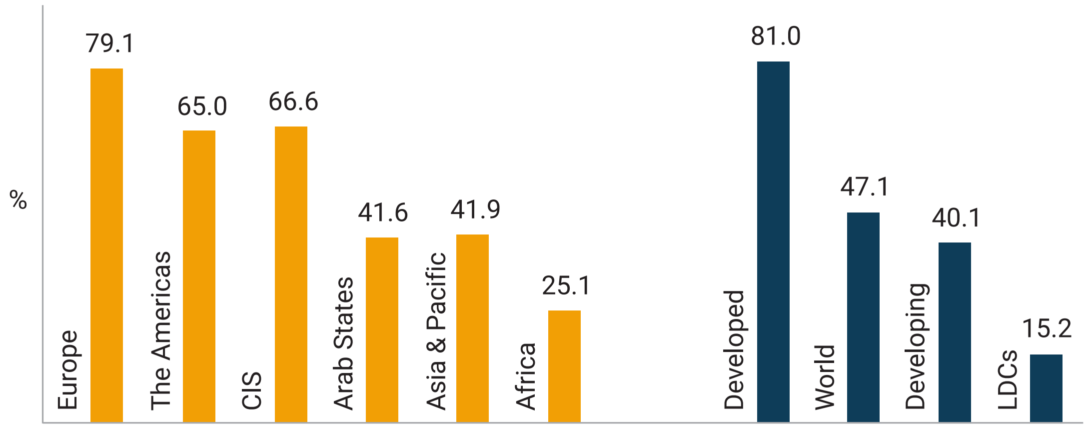



***Figure 2.6*** *Percentage of individuals using the internet (ITU, 2016)*

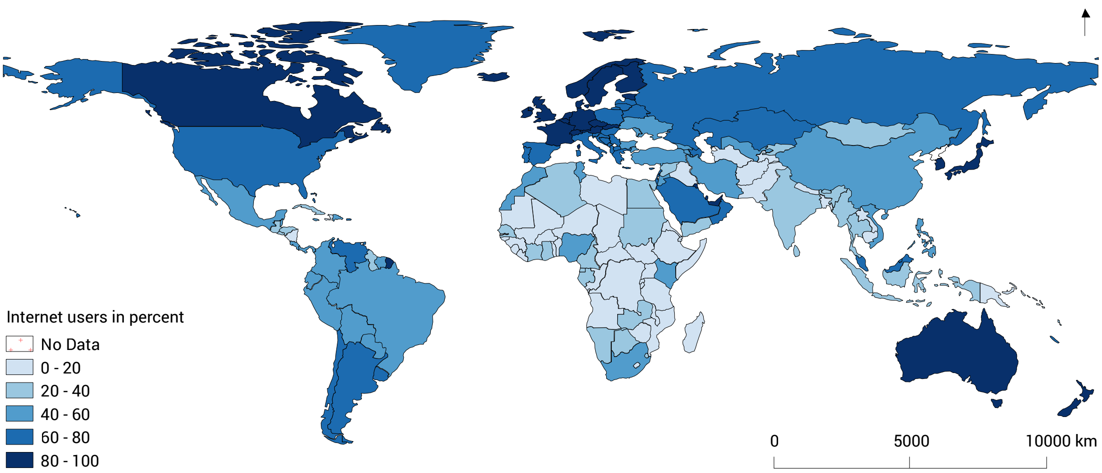



***Figure 2.7*** *Internet users per country (ITU, 2015)*

Nielsen (2006) criticises that the digital divide is often limited to the economic divide, meaning that people (as individuals or nations) cannot afford the costs of purchasing devices and infrastructure of modern technology and are therefore left behind. He claims it is not just difference in infrastructure and wealth that causes participation inequality, but the usability of technology, "many people couldn't use a computer even if they got one for free." Even amongst computer users, many only scratch the surface of possibilities because often services are too complicated to understand.

Goodchild (2008) criticises the usability of geobrowsers and claims the designers have not followed best practice in software engineering to build system functionalities based on user requirements. A more recent and comprehensive usability evaluation of geobrowsers is currently being carried out by Hamerlinck (2016). The need for a Digital Earth has been expressed by Al Gore almost 20 years ago, when he talked about the then science fiction like future scenario of a Digital Earth (see section 3.2.2). In this visionary speech, Gore made the following statement:

> *The data needed for a digital globe will be maintained by thousands of different organizations, not in one monolithic database. That means that the servers that are participating in the Digital Earth will need to be connected by high-speed networks. Driven by the explosive growth of Internet traffic, telecommunications carriers are already experimenting with 10 gigabit/second networks, and terrabit networking technology is one of the technical goals of the Next Generation Internet initiative. The bad news is that it will take a while before most of us have this kind of bandwidth to our home [...].*
> (Gore, 1998: p.90)

It will certainly take a while before most people have private access to bandwidths of 10 gigabit/second. These magnitudes of speed seem unnecessary given that modern digital globes use streaming methods to deliver uninterrupted user experiences (see 3.3.1). Nevertheless, internet connectivity is required to access background imagery in all modern geo-browsers. Some of them provide the possibility to cache data, but do not give access to locally store base map data due to corporate licensing. Gore makes a point in the above quote that data for a Digital Globe shall be maintained by thousands of different organisations. Currently, it is a few private corporations that hold all rights to software and most of the data. Craglia et al. (2012) wrote a position paper that re-evaluates Al Gore's early ideas in the light of the developments 13 years later. They claim that no single organisation can on its own develop all the aspects of a Digital Globe. Instead, it is essential to develop a series of collaborations at the global level to turn the vision into reality. In the paper, they strongly highlight the need for citizen involvement and the case for VGI. However, their suggestions are built on the assumption that by 2020 "(...) most people and things will be on line all the times." (Craglia et al., 2012: p.18). Despite the general development of moving services and storage to the cloud, there is a need for local storage in order to enable offline use and to overcome participation inequality. Haklay (2012) argues that a common practice in literature is to mention issues on the digital divide before either ignoring it throughout the analysis or to expect it will solve itself through technological diffusion over time. Being serious about accessibility of information means to not rely on strategies that half the world, including Mbendjele hunter-gatherers in the Congo Basin, cannot access.

### 2.3.2 Unmapped Territories

Taking one step back from data access is the mere existence of data. The most accurate and up-to-date topographical map of the Republic of the Congo is from a survey carried out in the 1960s by the National Geographic Institute (Institut Géographique National - IGN) based in Paris. Figure 2.8 shows an example of such a map. The logging town Pokola is shown at actual map scale 1:200,000, illustrating the lack of detail provided by the most accurate survey available. This map, and others of its kind, depict regions of the Congo Basin as dense forest land that seem unsuitable for living. The green that dominates the map visually is only broken here and there by a small clearing, a thin stream, river or by marshy and semi-flooded areas.

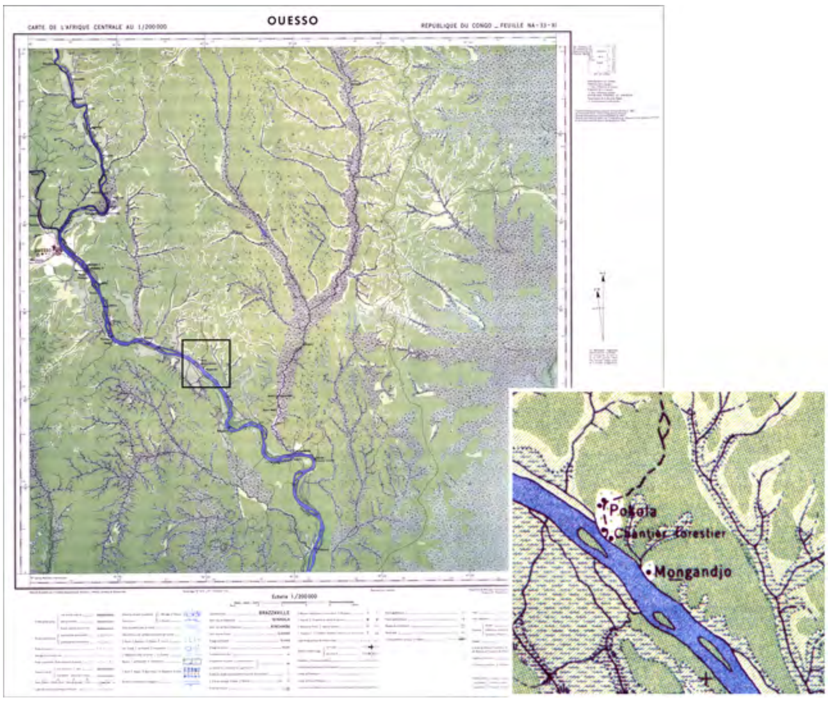



***Figure 2.8*** *Map of Ouesso region (IGN, 1963)*

What is often difficult to imagine in the industrialised part of the world is that not every single street in every city in the world, let alone in rural areas, has been mapped. The major challenges that this imposes on disaster response organisations, such as Médecins Sans Frontières (MSF), is to pinpoint locations of people that require immediate help, has led to a project called 'Missing Maps' – a collaboration between the American Red Cross, the British Red Cross, Humanitarian OSM Team and MSF. The ambitious aim of this project is to create a free and open-source data set containing every single settlement on Earth (Michael, 2014). Their approach is to have volunteers remotely trace the outlines of buildings, roads and rivers over satellite images. These outlines are later verified and named by volunteers on the ground. Despite licensing issues concerning the tracing of proprietary satellite imagery, companies such as Microsoft (Leson, 2015) and DigitalGlobe/Mapbox (Mahon, 2015) have proven collaborative, given the good cause. Even if this project succeeds in mapping every settlement, road and river, there are areas that do not fall into named categories, such as deserts and forests. It seems highly unlikely that all forests will be mapped on a granular basis in the near future. In order to visualise forests in detail, high-resolution imagery is currently the most suitable solution.

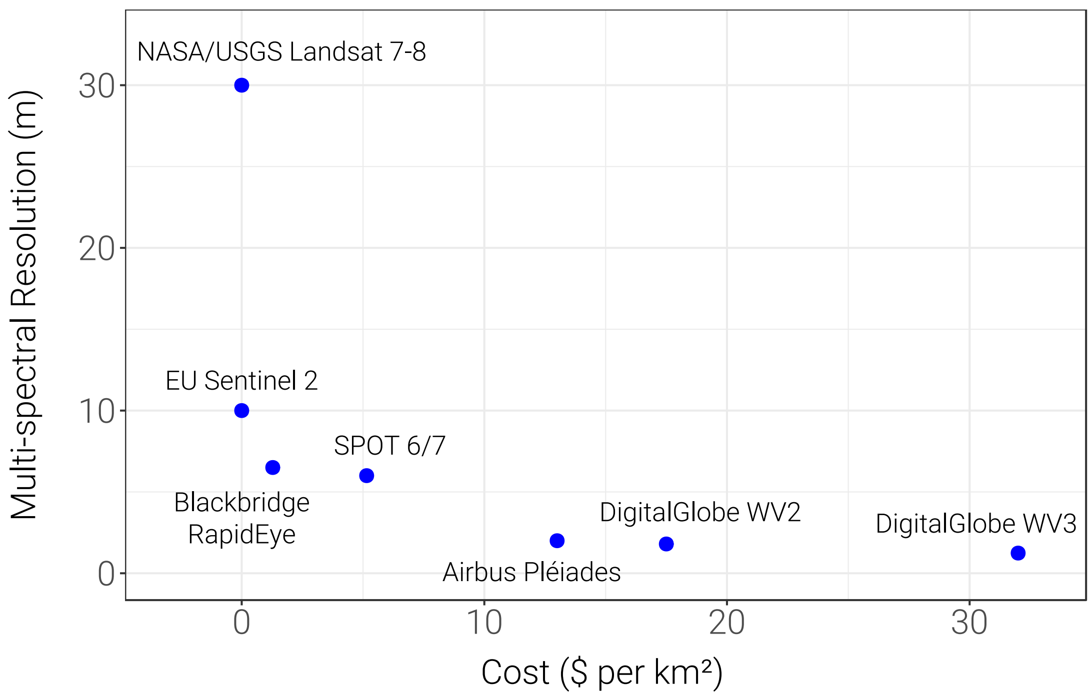



***Figure 2.9*** *Cost versus spatial resolution (World Bank Group, 2016b)*

Current Earth observation satellites are listed in Table 3.1 in section 3.1.1. The three satellites operated by the National Aeronautics and Space Administration (NASA) or the European Space Agency (ESA) are open data, meaning that it is free to download processed and use geo-rectified orthophotos for any purpose. They are at the same time the satellites with the lowest multi-spectral spatial resolution. Figure 2.9 illustrates the correlation between the cost of satellite imagery and the spatial resolution of the data. The costs indicate an order of magnitude and can vary depending on various factors, such as extent or distribution rights. Licensing can impose limitations on usage and shareablitity of data. High-resolution products are typically restricted to be published as rendered maps (World Bank Group, 2016b).

A review of current Earth observation satellites reveals that Sentinel 2 of ESA's Copernicus mission, currently provides the highest spatial resolution, freely available optical satellite data. It captures scenes at a multi-spectral resolution of 10 metres, which can be downloaded through the Sentinel Data Access Service by Catapult (2017). There are no current plans of launching a non-commercial satellite with a resolution higher than 10 metres.

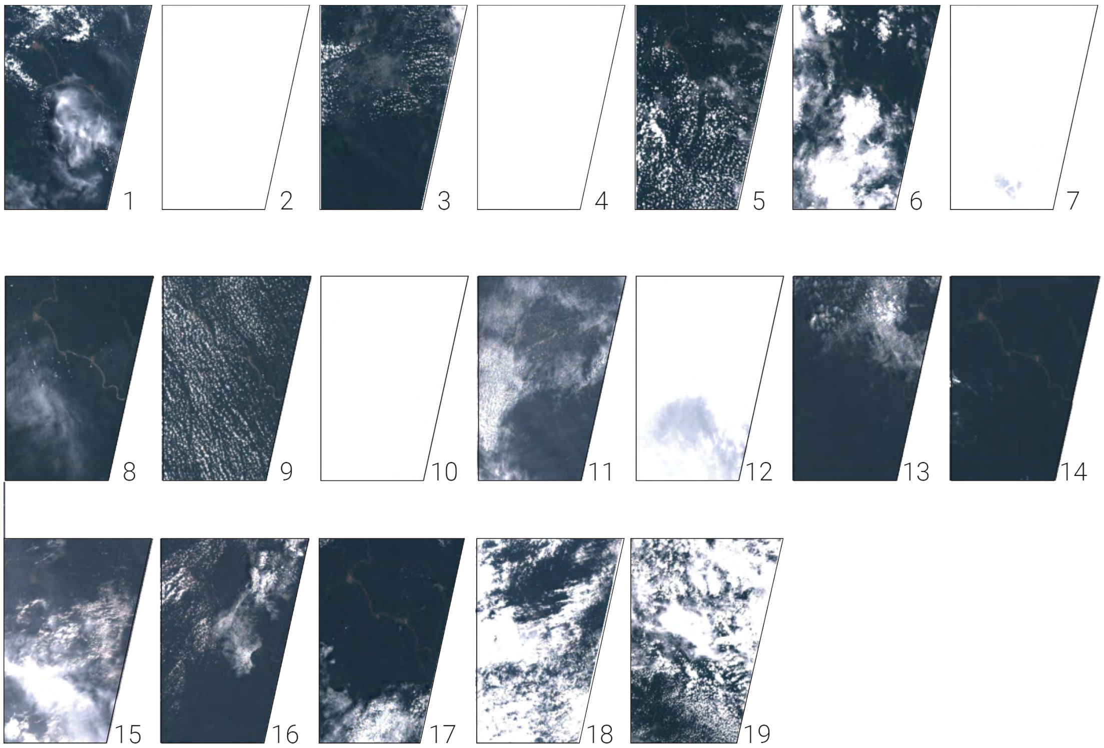



***Figure 2.10*** *Sentinel 2 – cloud cover*

Figure 2.10 shows thumbnail photos of all scenes captured by Sentinel 2 during one year (June 2016 - June 2017) for the area covering the field sites for this research (see figure 5.2). A total of 19 satellite images have been produced for the given time frame and location, of which five (2, 4, 7, 10, 12) are entirely covered by clouds. In merely three of the images (8, 14, 17), the areas of interest are at all visible. Image scene number 14, which shows the highest ground visibility, has been downloaded in full resolution.

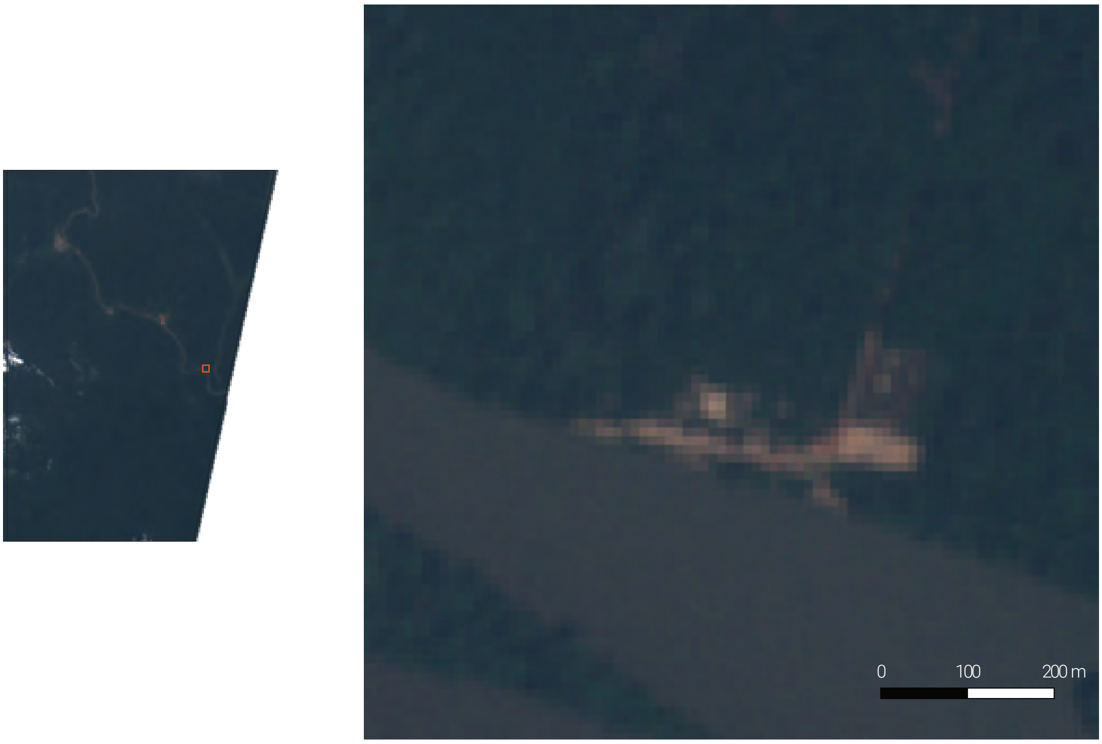



***Figure 2.11*** *Sentinel 2 – 10m ground resolution*

Figure 2.11 shows the field site Matoto at a higher zoom level, with one image pixel representing 10 metres on the ground. While it has proven possible to obtain relatively cloud-free scenes of free satellite data, at a spatial resolution of 10 metres, it is not possible to distinguish single features with trees blending into green 'forest pixels' that are hardly distinguishable from one another.

An alternative to using satellite imagery is to commission the acquisition and processing of custom data. Acquisition costs of aerial photography consist of a base cost for mobilisation of aircraft plus a charge per image. Konecny (2014) estimates the mobilisation costs between \$3000 - \$5000, depending on season and given the close proximity to the survey area. Mobilisation costs may be considerably higher if the aircraft has to be transported to a distant region. For the analysis, prices depend on the level of workflow automation as well as labour costs of a specific country.

Price, resolution and licenses are not the only limitations to satellite imagery. More often, the problem is the availability of required data (Koh and Wich, 2012). As shown above, in the tropical zone it is rare to obtain a cloud-free scene acquired by a satellite. Companies, such as Google, can for the most part remove clouds from their data products through resource heavy mosaicking algorithms. Through contracts with image providers, they have access to most available imagery, which they process using thousands of servers (Gorelick, 2013). Google Earth Engine is designed to enable petabyte-scale computation of geospatial datasets. In order to compute the second generation of a cloud-free mosaic of the world, Google servers processed more than 700 trillion individual pixels (Herwig, 2016). While it is possible for users to access Google Earth Engine and harness this computing power, the provided data catalogue is restricted to open data, such as Landsat or MODIS (Gorelick, 2013).

### 2.3.3 Linguistic Challenges, Literacy and Educational Heterogeneity

The majority of ICT systems, including mapping software, use the English language in a written form as the method of information exchange. Present day estimates put the number of people living on our planet at around 7.2 billion individuals, all of whom are using one or often multiple forms of human language to communicate within their environments. Languages evolve over time, incorporating foreign elements and sometimes dying out completely. According to Lewis et al. (2016) there are 7097 languages spoken today. The number, however, cannot be pinned down as it is constantly changing due to the dynamic nature of languages.

A breakdown of this number shows that a third of the languages are currently spoken by less than 1000 people worldwide and are therefore classified as endangered. 23 languages are used as a first-language by half of the world's population while certain countries have several hundreds of languages (Lewis et al., 2016). English is the language that reaches most people around the globe. Linguist Crystal (2012) estimates the number of all English speakers at about 1.5 billion, including 750 million first and second language speakers and approximately the same amount of people speaking English as a foreign language. This number then indicates that about one fifth of the current population speaks and understands English, meaning that four fifths do not. This fraction of the world is therefore excluded when English is used by ICT systems as the language of interaction. Taking this into account, there is an evident case for adapting ICT systems to local languages via translations. At the same time, this cannot be considered as a universally inclusive solution either as it ultimately leads to participation inequality, in that it does not address the illiterate and non-literate population.

Most ICT systems rely on written text as the method of information exchange. In addition to language barriers between native and foreign languages, illiterate and non-literate people need to be accounted for. In fact there are 758 million people (14.7%) aged 15 and above worldwide – two thirds of whom are women – who are unable to read or write according to the latest literacy figures of UNESCO Institute of Statistics (2014). Looking at the global distribution of the illiteracy levels reveal that the situation is worse in Sub-Saharan Africa (figure 2.12). The literacy rate correlates with the Gross Domestic Product (GDP) per country as well as the remoteness of social infrastructure, such as schools and hospitals (Ohenjo et al., 2006).

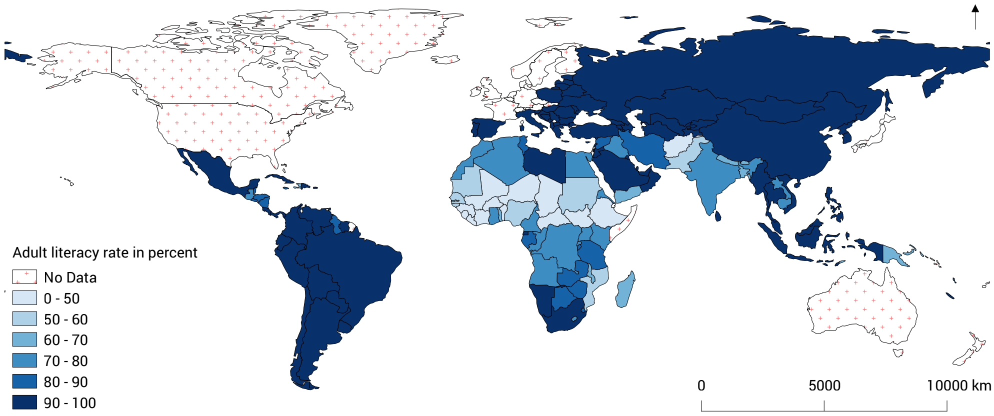



***Figure 2.12*** *Literacy rate (15+ years) per country (UNESCO Institute of Statistics, 2015)*

Figure 2.12 shows a map illustrating official adult literacy rates per country. The underlying data was collected and published by the UNESCO Institute of Statistics (2015). It represents the percentage of the population age 15 and older who can read and understand as well as write a short, simple statement relating to their everyday life. 59% of the literacy data displayed in the map are from the year 2015. For countries, where no surveys were carried out in 2015, the latest available information was used in the range between the years 2000 and 2014. The map shows that especially in Africa and parts of Asia it cannot be assumed that the written word is a method of reaching the masses. In 12 African countries and Afghanistan the literacy rate is lower than one in two people. These numbers are based on survey projections and, therefore, do not account for remotely based, non-literate communities.

This picture gets even more complex when further forms of illiteracy are taken into account such as innumeracy and visual illiteracy (i.e. extracting meaning from images), all of which are taught in the education system to a certain degree. In countries, however, where formal education is not strictly enforced, people reach adulthood without attaining the basic ability to read and write. In indigenous communities, another factor to be considered is the complete absence of a language's written form.

Figure 2.13 illustrates the variation in education attained by different population groups in the Republic of the Congo. The data was collected in the course of the Demographic and Health Surveys (DHS) carried out in the RoC in 2012, published by Deon (2016). During a visit to the indigenous village Sembola (see section 5.2), a research assistant pointed out that "women typically get pregnant at a very early age and even if they visited school before, most will not return once they have a baby." The graph supports this claim. Male and female children are roughly neck and neck in school attendance up until they reach the fifth grade. It is around this time that young women reach sexual maturity and the curve representing them in the chart starts plummeting, so much so that by the 9th grade their attendance in school has dropped by nearly 40 percent. The number of male students attending school also diminishes but 'only' by 28 percent.

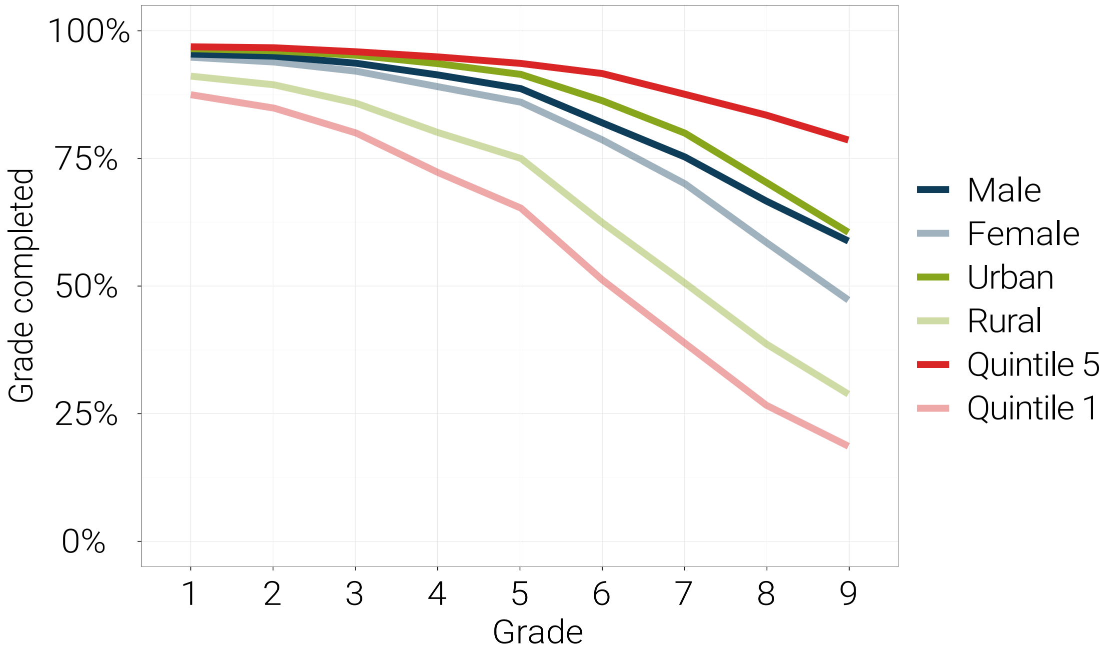



***Figure 2.13*** *Attained education (Deon, 2016)*

While there is a difference between the two genders, as shown in figure 2.13, the gap increases even further when comparing urban with rural populations. Already at the start of their education, 5 percent less pupils make it to school from rural areas and only 29 percent reach ninth grade. This is a considerable value compared to the urban population's 60 percent who finish school. The difference becomes even more striking when comparing quintiles of the two extremes – the rich and the poor. This mix of languages, varying levels of illiteracy and education call for a unique approach to create an ICT system that is inclusive to the above described heterogeneous population.

## 2.4 Intelligent Maps Overview

Local forest people have shown interest in participating in mapping projects in order to prove their existence and to demand rights over forest usage (Lewis and Nelson, 2006). Intelligent Maps, a project by the ExCiteS research group, addresses this interest by engaging indigenous people in collecting, sharing and analysing spatial data, while also studying community participation in these activities. The aim of the project is to extend participation in environmental management beyond data collection. The development of a novel, socially and culturally accessible GIS could provide communities with an empowering tool to support environmental governance and social-environmental justice. The Brundtland report acknowledges that:

> "An industry may get away with unacceptable levels of air and water pollution because the people who bear the brunt of it are poor and unable to complain effectively. A forest may be destroyed by excessive felling because the people living there have no alternatives or because timber contractors generally have more influence than forest dwellers" (WCED, 1987: p.46).

Mapping of indigenous lands to secure tenure, resources and to empower cultures has a long history, with its roots in Canada and Alaska in the 1960s (Chapin et al., 2005). Lewis (2012) argues that traditional Participatory Rural Appraisal (PRA) mapping techniques, such as sketch mapping (Chambers, 1994; Peluso, 1995), are lacking in persuasive power due to their informal look and poor precision. Recent advances in technology and Geographic Information Systems (GIS) enhance the accuracy, speed and complexity of geographic visualisation. Complexity, in this case, means both information richness and complexity of use. Today, numerous Geovisualisation (GVis) tools exist that aim to enable users to gain insight into the meaning conveyed by the data and to facilitate informed decision making. However, their effectiveness is often limited by the lack of a comprehensive approach towards considering human needs and exploring their abilities (Minghim and De Oliveira, 1996). Desktop and web-based GIS are often difficult to use, even for experienced and frequent computer users (Davies and Medyckyj-Scott, 1994; Nivala et al., 2008; Stehlíková et al., 2015). This PhD research forms part of Intelligent Maps by specifically addressing the questions of how to create suitable maps and whether digital maps and mapping tools are understood by people who have no culture in reading maps or using technology.

### 2.4.1 Theoretical Gaps

This section identifies the theoretical gaps in the literature concerning PGIS, GISc and Human-Computer Interaction (HCI) addressed in this research within the framework of Intelligent Maps. Literature in the field of PGIS commonly describes the procedures and outcomes of community mapping practices (Rambaldi et al., 2006; Corbett and Keller, 2006). Many methods fall within the category of community or participatory mapping, ranging from ephemeral mapping, where people use any available material to draw maps on the ground to technically sophisticated PGIS practices with accurate reference maps and GPS positions (Rambaldi et al., 2006; Warren, 2010). A classification of ten common participatory mapping practices has been carried out by Pánek (2015), who created a web-based tool that for choosing the optimal method for a specific project within the realm of participatory mapping. Although less geographically accurate methods, such as ephemeral mapping or sketch mapping, are commonly deployed to gather local knowledge and facilitate discussion within communities they are less suitable for linking community members with policy makers (Chapin et al., 2005; Martin et al., 2012; Burini, 2012). This research is part of a bigger vision that aims to enable communities to actively contribute to decision making processes and thus it is focused on geographically accurate, reproducible and interoperable methods.

Training is required to use technologically sophisticated approaches which puts an outsider in a dominant, knowledgeable position. Researchers commonly argue, that it can be disempowering to use complex, cost-intensive technology (Rundstrom, 1995; Dunn et al., 1997; Abbot et al., 1998; Chambers, 2006). Such arguments imply that ICTs and GIS, are essentially inaccessible and inherently controlled by outsiders and have therefore limited value to remote and rural communities.

In contrast, Blaser et al. (2004) argue that preventive development practices are often in the way of indigenous peoples' 'life projects', a term used to describe indigenous agency. Moïse (2011) further explains that the prevalent portrayal of pygmies as victims under the domination of the powerful (Woodburn, 1997; Rupp, 2003) overshadows the picture of pygmies as historical agents who play an active role in shaping their own life conditions. He further highlights that Baka people have often proved to be creative entrepreneurs who are willing to take the initiative if new opportunities arise through the interaction with outsiders.

When reporting PGIS mapping activities, authors write statements, such as "The villagers could easily relate to aerial photographs, but experienced some difficulties in respect to scaling." (Rambaldi et al., 2006: p.28); "In parallel came the discovery that local people could readily interpret black and white aerial photographs" (Chambers, 2006: p.3) or "The community interacted fairly well with the new technology and information. Villagers were generally able to interpret aerial photographs rapidly and effectively, with initial assistance from a facilitator" (Jordan, 2002: p.238). While all of these statements are qualitative in nature, the authors convey a positive message towards the understanding of maps. At the same time Corbett and Keller (2006: p.21) claim that "GIS requires a steep learning curve, a strong commitment to keeping software and operator skills current, and a deep wallet". While accepting the concerns about outsiders taking control, during the literature research there was no project identified that tested the understandability of culturally adapted mapping interfaces. GIS commonly seems to exclusively refer to complicated software packages as opposed to "system[s] for storing and manipulating geographical information" (Oxford University Press, 2017) that can be adapted in a user-centred fashion.

This research argues that a genuine understanding of the system can increase the feeling of ownership and decrease the reliance on outside experts. Importantly, geographic accuracy and interoperability with other software packages as well as adequacy of use are vital for empowerment. The question remains whether understanding of map usage in order to communicate location based issues to stakeholders, such as logging companies, NGOs or certification agencies can be achieved through adaptation of mapping software.

Despite much prior and ongoing research effort in the field of cartographic visualisation, it is not yet clear what kind of visualisation has the power to facilitate map understanding and information management for novice users. Cognitive map design research aims to understand human cognition to improve the design and consequently the use of maps (Montello, 2002). Particularly in the mid to late 1900s cognitive map research has been established as a systematic sub-discipline of cartography. Crucial for this developments was the publication of *The Look of Maps* by Robinson (1952). It gave way to empirical studies of graduated circles (Flannery, 1956; Crawford, 1971) as well as eye movement studies during the reading of maps (Castner, 1964; Steinke, 1987). Theoretical studies evolving from the new paradigm included the development of the communication model as a scientific framework.

The communication model, (see section 3.2), is a much discussed theory in the field of cartography and its name implies relevance to this research as, fundamentally the idea is to use maps as means of communicating location specific issues. The basic principle of the theory, as it was defined in the late 1960s, is that the cartographer has the role of the all-knowing expert who decides which kind of 'message' or 'information' is to be transmitted to the passive recipient. Guelke (1976) argues that the theory, which stems from the field of electronics, where information is transmitted to the receiver does not apply in cartography. Instead, it strongly depends on the usage of a map whether a specific visual feature should be regarded as (unwanted) noise, (intended) message or both. Lobben et al. (2015) argue that the very idea of transferring information as opposed to contextually and culturally meaningful knowledge is questionable. Many authors, including Poore and Chrisman (2006); Haklay and Jones (2011); Robinson and Petchenik (1975) criticise similar aspects regarding the all-knowing cartographer creating a static visualisation for a passive, unfamiliar user.

It is also the traditional roles that this research is challenging. Following an Extreme Citizen Science approach as defined in 2.1, the use of the map is fundamentally different from how it is discussed in most of the cartographic literature. It is no longer differentiated between the roles of the cartographer and the map user, but citizens generate as well as consume georeferenced, thematic data, whereas the reference map is created by a GIS professional. The citizens are the ones with all the thematic expert knowledge but might be novice to GIS. The GIS professional on the other hand has only limited control over the map visualisation that needs to be defined as a set of algorithmic rules without knowledge of the data to be displayed and ways users will interact with the final, or possibly ever evolving, product.

As pointed out by Montello (2002), much of the empirical map reading studies emerging after 1950 were focused on thematic maps (Robinson, 1982), including the popular studies on graduated circles. During the late 1970s various authors, such as Petchenik (1977); Olson (1975); Guelke (1976) criticised the inadequacy of researching symbols in isolation and called for a more holistic approach to researching map design (Montello, 2002). If there is a message being delivered via a map presentation, then it is a result of complex and subjective processes, such as selection, classification, generalisation (Haklay and Jones, 2011) as well as interpretation by individuals possessing prior knowledge (MacEachren, 2004).

Haklay and Jones (2011) discuss Guelke's (1976) paper on the communication theory and its relevance transferred to the context of GIS. The changes in the media of creation and delivery, alongside the introduction of interactive and animated maps, have altered the scope of some of the original arguments. The user is granted some more control over which information is to be displayed, what scale to zoom to and might even have access to change orientation or map symbology. These advancements, however, force the user to interact and engage with technology. Map symbology as well as eye-tracking are ongoing research topics in recent publications (Brychtova and Coltekin, 2016; Franke and Schweikart, 2017), however, the medium has changed from static paper maps to digital maps or GIS. This development has given new rise to traditional cognitive cartography topics such as way finding and self-location (Kässi et al., 2013; Jokinen and Saariluoma, 2015), regarding various kinds of perspective, such as 3D (Tüzün et al., 2016), Augmented Reality (Goh et al., 2015) or Virtual Reality (Morganti and Riva, 2014).

Regardless of perspective, these studies typically deal with participants that are learning a new environment through a spatial representation. Little research has been done on people who have never seen a map before. Bluestein and Acredolo (1979) and Blaut et al. (2003) carried out map reading experiments with children, who have their inexperience in using maps in common with forest people and that they have not (yet) gone through formal school systems. But there are fundamental differences in their cognitive skills as well as knowledge of their real environment. Due to their lifestyle, the pygmies have an astonishing sense of direction and extensive knowledge of forest topography. They travel huge distances through the forest visiting clan relatives and seeking work. Some members have been reported to have moved up to 800km in one year (Lewis, 2002).

The fact that the potential users considered in this research are not only new to map visualisations but also to digital technology, suggests the utilisation of HCI methods. However, disciplines of HCI follow strict protocols for systematic observation and measurement. In the urban and developed context where these methods were created it makes much sense to follow rigour protocols and implement improvements in an iterative manner. It is often not possible to carry out textbook style User-Centred Design (UCD) in remote communities. Besides the increased costs, visas and other policies as well as cultural differences pose challenges. These issues will be discussed in section 8.2.3.

Roth et al. (2017) outlines four interdisciplinary influences on the ways that user studies are designed in cartography, drawing samples from Psychology (Olson, 1975; Liben and Downs, 1993; Wiener et al., 2012), Geography (Crampton, 2009), HCI and Usability Engineering (UE) as well as information visualisation and scientific visualisation. All named disciplines are hypothesis driven following a highly controlled approach to user studies with the goal of drawing generalised conclusions.

This research with its aim to empower marginalised communities to use digital maps is most related to the field of HCI and UE as the primary question to be explored is whether a technology-driven, cartographic visualisation ’works’. It does however differ from typical empirical user studies in digital cartography and UE, due to the difficulties in creating highly controlled lab experiments. Thus, the applied methodology borrows principles of Action Research, which uses systematic observation and data collection methods focused on real world problems and situations.

### 2.4.2 Technical Infrastructure

This section describes the approach developed by UCL’s ExCiteS group to create a socially embedded technical infrastructure that takes into account the specific challenges outlined in section 2.3. In this context, a data collection app was developed and optimised for data transmission and the UI was adjusted based on local people’s requirements. Prototype testing was carried out by different members in the field (see table 2.1) and the learnings thereof together with the gaps in theory inform the research questions, which are outlined in section 2.5.

The main outcome of Intelligent Maps is a GIS that allows users to securely upload data from their handheld devices. The conceptual technical configuration of the Intelligent Maps is shown in figure 2.14, with this research specifically contributing to the areas highlighted in orange.

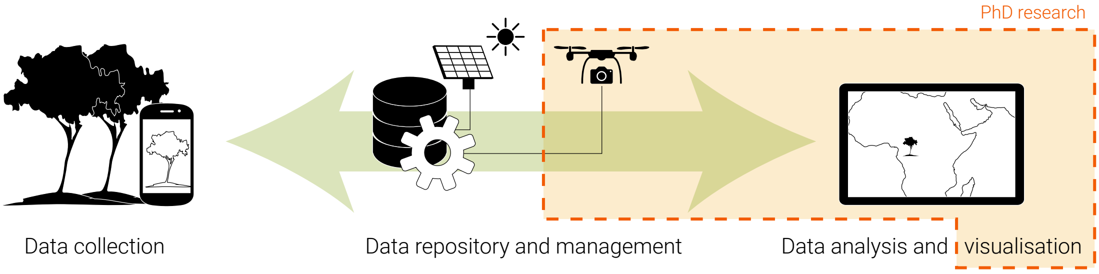



***Figure 2.14*** *Technical infrastructure for Intelligent Maps*

The left side illustrates data collection systems 'Sapelli' and 'Tap & Map', which are further detailed later in this section. In addition, it is envisioned to integrate other data collection suites, such as Open Data Kit (ODK) (Hartung et al., 2010), EpiCollect (Aanensen et al., 2009) or CyberTracker (Steventon et al., 2002) to ensure maximum flexibility in addressing the requirements of specific projects. The next element addresses the needs of data storage and data management. The GeoKey platform, developed by ExCiteS (Haklay, 2016), offers these functional capabilities but is currently geared towards technically literate people. The framework of GeoKey, however, was developed with Intelligent Maps in mind. A potential extension and development of the storage system will enable dealing with permissions, information protection, and sensitive data sharing necessary for Traditional Ecological Knowledge (TEK). GeoKey itself would run on a portable rugged server with little energy needs. This can be solved with a Raspberry Pi computer, powered by solar energy. Finally, the information collected in different devices and stored within GeoKey will be shared and visualised on a tablet computer running the Intelligent Maps client software. On this, the user will be able to visualise their data together with data from other users based on personal permissions. Over time, repeating patterns will begin to emerge indicating particular environmental trends. Significantly, the representation will be one that is meaningful to the users.

In 2006, Lewis and Nelson (2006) initiated a program together with the logging company Congolaise Industrielle des Bois (CIB), who are working towards certifying their entire operation (1,300,000 hectares) in the northern part of RoC. With that goal in mind, the company needed to develop procedures to minimise impacts of timber extractions on both the ecosystem as well as the indigenous people inhabiting the forest. In order to achieve this, a software company was contracted to develop a mapping tool featuring an iconic UI for use by non-literate people to map their key resources. PDAs and separate GPS receivers were used, enabling forest inhabitants to record their resources and potential logging violations (see figure 2.15). In order to make a recording, the users were navigating through an icon-based decision tree (Lewis, 2012; Lewis and Nkuintchua, 2012). A similar project was set up aiming to monitor the harmful activities of commercial poachers. In addition to the issue of over-hunting, a further goal was to record harassment against local people by government-run ecoguards, supposedly responsible for controlling poachers. In 2011 the ExCiteS Research Group took up Lewis' icon-based approach and developed a mobile app, enabling non-literate, local communities to collect evidence on commercial poaching activities (Vitos et al., 2013).


***(a)*** *Decision tree icons* ***(b)*** *Mapping of felled tree*

***Figure 2.15*** *PDA based data collection (Photos by J. Lewis)*

The high cost of the then outdated PDA devices (£1,000 - £3,000), the need for external GPS receivers as well as the limited usability of the previous platform rendered the existing system unsuitable. In late 2012, the decision was made to implement a new data collection software in-house[2], due to the absence of an existing solution to meet the project's needs with regards to text-free, hierarchical interfaces and autonomous multi-modal synchronisation. An earlier iteration of the software was built on top of ODK,

[2]This section describes the joint effort of Dr. Matthias Stevens, Michalis Vitos and the author, Julia Altenbuchner, to develop a new data collection platform.

which required verbose project definition forms that were difficult to maintain. The effort to entirely rebuild the data collection app was necessary to ensure maximal flexibility in project design as well as automatic and multi-modal data sending capabilities (Stevens et al., 2013). An important aspect for the design of the data collection software, was to run on low cost, off-the-shelf mobile devices and to not require any specialised hardware. With logging companies building towns in the forest, they bring infrastructure with them, such as GSM-based networks that can serve as transmission carrier. The new data collection software was named 'Sapelli', after a tree species that hosts caterpillars (see figure 2.16a). The caterpillars are a valuable protein source for the Pygmy communities (see figure 2.16b) but at the same time the Sapelli tree is the main commercial species extracted by logging companies.

***(a)*** *Sapelli tree (Sharp, 2008)*

***(b)*** *Caterpillars as protein source (photo by J. Lewis)*

***Figure 2.16*** *Resource conflict around Sapelli tree*

The first iteration of the Sapelli Collector software consisted of three main components: a data collection app (with integrated data sending service) for Android devices, another Android app (called the 'Relay') to forward SMS messages, and a server application to receive and store data. This early version of Sapelli has been deployed in a project carried out in collaboration with the NGO Forests Monitor, aiming to support forest-dependant communities in the Republic of Congo that are affected by industrial forest exploitation (Stevens et al., 2014). The UI of this version was restricted to the visualisation of pictorial decision trees with the option to augment observations with photographs, audio recordings and/or GPS locations. As per the requirements of the international NGO, Forest Peoples Programme, Sapelli's features were later extended to include textual forms in order to cater for scenarios where NGO staff map resources together with forest people. In this scenario, the staff member fills out a meta data form and then hands over the device to the locals for the actual resource mapping.

**Data Transmission**

Given the context of the remote rainforest, an optimised data transmission mechanism was an important aspect in the design of a new collector software. Automatic data transmission is challenging in remote areas with little network infrastructure. In regions close to logging towns, however, people tend to get occasional GSM connectivity. Sapelli offers a multi-modal data transmission mechanism that is optimised to cater for different connectivity scenarios. In order to send data via SMS, records are serialised in a binary format which is heavily optimised for space. They are grouped together in transmissions, which are further reduced in size by applying the best performing compressions algorithm on the fly. Due to the large file size, the transmission of optional media attachments is not possible via SMS. These can be locally exported and later associated with their corresponding records. If there is no data carrier available in an area, records can be exported to a local memory card on the phone. In situations where internet connectivity is accessible, data is sent to a server via Hypertext Transfer Protocol (HTTP) requests.

By design, all data transmission should happen in the background and not require user interaction. Therefore a service is set up that automatically checks for connectivity at scheduled intervals and sends off the data when possible. Implementing this strategy, the data transmission system underwent two iterations. Initially, when GSM network connectivity was detected, text-based information, such as timestamps, decision tree selections, coordinates, etc.) were forwarded to a 'relay' phone, which posted the data to a central server via internet connection. The features of the server component were limited to receiving and storing data. Due to the unreliability of the SMS forwarding relay phone, this transmission system was deprecated.

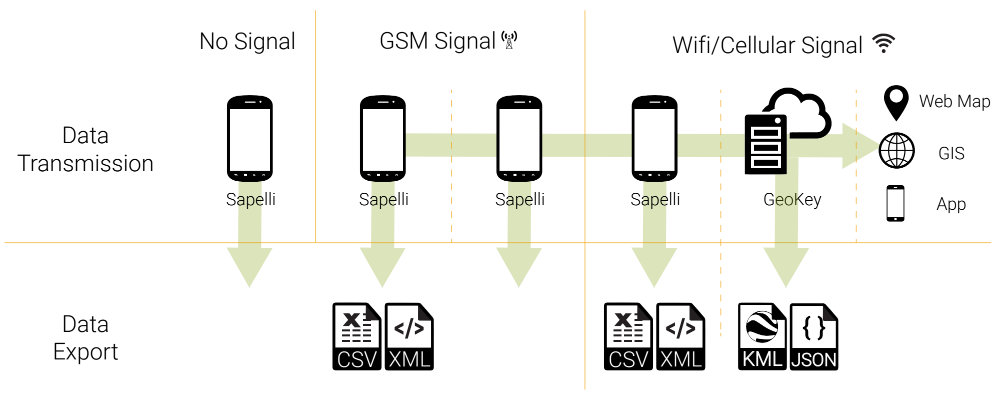



***Figure 2.17*** *Data transfer architecture*

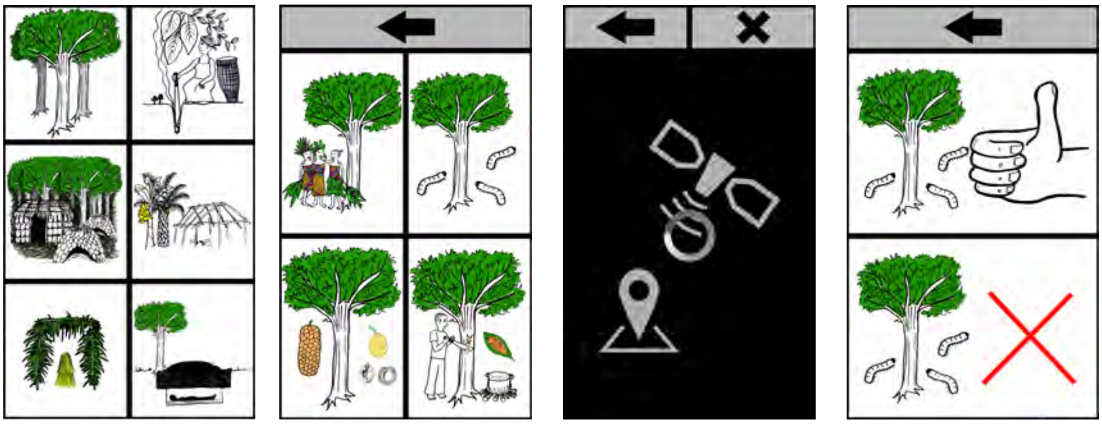
A new system, (see figure 2.17), was designed that is capable of sending data from any Sapelli app to another via SMS. This way data can be accumulated, locally exported to a file or forwarded to a server from any device. Additionally, an HTTP connection to GeoKey was added. GeoKey (Haklay, 2016) is a web-based, open source platform that serves as a connecting point between data collection and data utilisation by providing a server-side infrastructure to receive, store and disseminate geographic data collected by citizens. This way, any Sapelli client that is connected to the internet can send data records, including file attachments to a web server.

**Survey Elements & Design**

Due to the focus on low and non-literate users, the initial priority was to make it as straightforward as possible to build pictorial decision trees and icon-driven interfaces. The inadequacy of the survey description languages used in other platforms (e.g. the XForms-derived format used in ODK) led to the design of a new proprietary format based on Extensible Markup Language (XML). Decision trees, or conditional constructs in general, are built by nesting XML nodes, where the outermost node represents the first decision that must be made. Users navigate the decision space by repeatedly selecting a child node until they reach a leaf node, which represents a final selected value. This hierarchic description makes the structure of the decision space immediately apparent by looking at the XML code. Capturing of photos, audio recordings and location (with GPS coordinates) have been supported since the release of the first prototype version. To allow for a hybrid usage of literate and non-literate people, standard digital form elements like text fields, check boxes, radio buttons, drop-down lists were added. These text-based elements can be grouped together on the same screen. Sapelli has been further extended to allow for information dissemination in addition to its information collection capabilities. Therefore UI elements are added that support HTML websites that can be locally served from the device.

**User Interface**

The decision tree UI of the Sapelli application is a minimalistic, entirely graphical, full-screen interface in which icons are arranged in a grid layout (figure 2.18). By tapping one of the icons, the consequent screen defined by the decision tree hierarchy appears (figures 2.18a, 2.18b). If desired, navigational buttons can be added. Typically they are displayed at the top of the screens consequent to the home screen and allow the user to correct unwanted actions or cancel the current observation. Once the last icon of the current record is tapped, the user either returns to the home screen or leaves the application (as specified in the XML-based project definition). Similar minimalistic UIs have been designed to add photo or audio attachments, which show a single button to execute the relevant action. After taking a photo, the user is given the option to either save or discard it. The scanning process for GPS signal starts without user interaction. If no GPS fix has been obtained by the end of the observation, a waiting screen will be shown (figure 2.18c). Sapelli projects typically end with a screen, which allows the user to save or discard the current record (figure 2.18d). All project set-up and transmission settings are configured once and do not require further user interaction.



***(a)** Level 1* ***(b)** Level 2* ***(c)** Waiting for GPS fix* ***(d)** Confirmation*

***Figure 2.18*** *Sapelli decision tree example (icons by G. Conquest)*

### 2.4.3 Prototype Testing and Scoping Mission

A field visit was planned when the development of the initial Sapelli prototype was finished. This way it could be presented to the communities in order to receive feedback for both the software and the project design. Five researchers visited eight camps over a period of six weeks.

***Table 2.1*** *Scoping mission*

| Community | Ethnic groups | ExCiteS delegation | Length |
|---|---|---|---|
| Bolozo | Bantu (Bakwele) | Conquest[1], Lewis[1], Stevens[2] | 1 day |
| Komo | Pygmy (Baka) | Conquest, Lewis, Stevens | 1 day |
| Attention | Bantu (Bakwele) and Pygmy (Mikaya & Baluma) | Conquest, Lewis, Stevens | 1 day |
| Poulani | Bantu (Bakwele) and Pygmy (Mikaya & Baluma) | Conquest, Lewis, Stevens | 1 day |
| Bangui Motaba | Bantu (Bomitaba & Bondongo) and Pygmy (Mbendjele & Kaka) | Conquest, Lewis, Stevens | 3 days |
| Sembola | Pygmy (Mbendjele) | Altenbuchner[3], Conquest, Lewis, Vitos[2] | 1 day |
| Longa | Pygmy (Mbendjele) | Altenbuchner, Conquest, Lewis, Vitos | 3 days |
| Sembola | Pygmy (Mbendjele) | Altenbuchner, Conquest, Lewis, Vitos | 1 day |
| Gbagbali | Pygmy (Mbendjele) | Altenbuchner, Conquest, Lewis, Vitos | 1 day |
| Attention | Bantu (Bakwele) and Pygmy (Mikaya & Baluma) | Altenbuchner, Conquest, Lewis, Vitos | 1 day |

*[1]Anthropology, [2]Computer Science, [3]GISc*

Table 2.1 shows the communities, in the order of visit, and the different members of the ExCiteS team that were present along with their scientific background. Members of the anthropology team were present throughout the duration of the trip. While the technical team mainly focused on the usability and appropriateness of software, the anthropologists were leading the discussions with the communities. In particular Dr. Jerome Lewis has established long-term relationships with local hunter-gatherer groups, which enabled easier access to communities and gave the project legitimacy from the viewpoint of participants. The approach for engaging with communities and introducing tools was adapted from projects conducted previously in the Congo Basin (Lewis, 2012), but is continuously refined in response to local conditions (Stevens et al., 2014). In each of the communities, the population spoke either Lingala, or the local forest language. The translation was facilitated by our local project partners and Lewis, who speaks the local Mbendjele language.

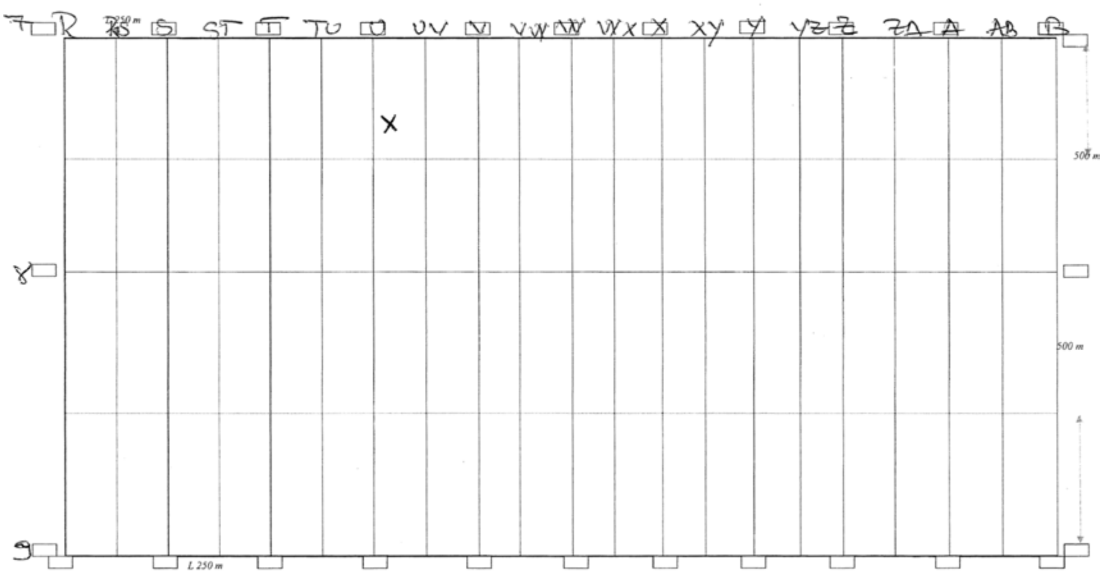
Upon arriving at a community, the ExCiteS group followed a FPIC process, in which the first step was to introduce themselves to the local population. The Intelligent Maps project was explained, followed by the question whether they were interested in testing the Sapelli collector. Consequently, everyone who had given their consent was invited to join the participatory process of introducing the decision tree icons, test the phones and eventually map nearby resources, shown in figure 2.19.

***Figure 2.19*** *Community engagement process*

During the scoping mission, a member of staff working for CIB outlined the procedure of carrying out local mapping consultations with forest communities. He explained that the company's social mapping group visits forest communities to have a consultation with them on which resources should be protected from commercial activities. Subsequently, these resources are marked with red paint and their location is recorded with a GPS receiver (figure 2.20).

On return to the office, these coordinates are overlaid on a map with the results being shown to the communities for validation and discussion (see figure 2.21). He further explained that these discussions allow community members to better understand the process and to learn to read the maps. When the inhabitants of Sembola were asked about the process of map consultation, it turned out that only few of them had ever seen such a map, and those who did stated that they did not understand it. Given the inadequate scale on which single trees are portrayed, reading these maps would be difficult even for map literate societies.

**Positionnement sur carte**




**Ressources et sites sensibles identifiés**

| Numéro | GPS coordonnées | | Parcelle | Ressource / site | Type | Statut | Nom | Usage |
|---|---|---|---|---|---|---|---|---|
| 001 | N: 0650685 | E: 0174137 | 7-8-U-UV | Arbre | Non exp | Medicinal | Essia (Bosso) | Bouanga |
| | N: | E: | | | | | | |
| | N: | E: | | | | | | |
| | N: | E: | | | | | | |

*Figure 2.20* *Identification sheet for resource protection by CIB*

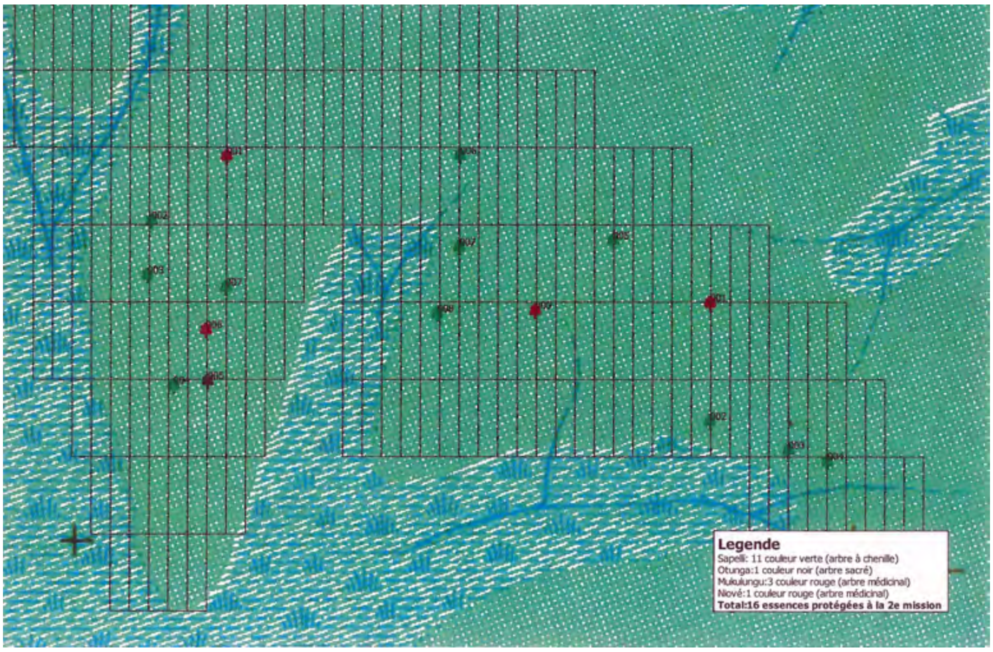


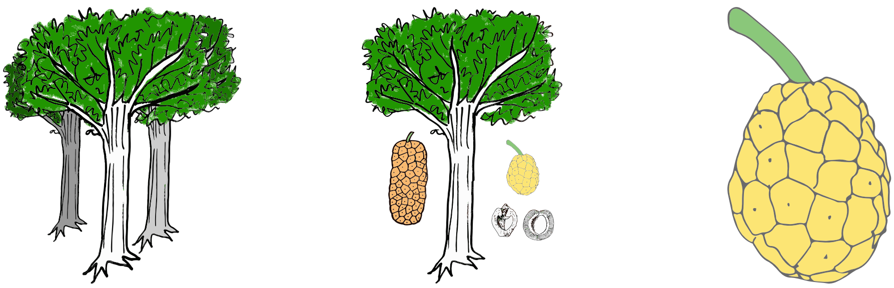

***Figure 2.21*** *Resource protection map by CIB*

The outlined procedure of the scoping trip was directly the subject of Michalis Vitos' research on the usability of the Sapelli UI. Furthermore, the field trip informed all team members of the way the project and technology were received and used by the communities. The first stage of a UCD approach is to observe the activities of potential users and identify their motives and needs (see Appendix 4.1). For this, it is crucial to observe the users in their natural environment, respectively the environment in which the product or service will be used. Thus, observations as well as discussions with communities and logging company employees served as the basis to form the Research Questions of this thesis.

All visited communities communicated their interest in testing whether 'machines' (as called by the translators) can help to collect and view their resources that need protection. They were specifically interested in sharing those maps with external, more powerful stakeholders. At this early stage, it was entirely unclear when and where exactly the project would proceed and therefore the researchers strictly made no promises in order to avoid false expectations.

**Lessens learned from Sapelli prototype testing**

When Vitos et al. (2017) carried out experiments to evaluate the usability of the Sapelli collector interface with Pygmy communities in the Republic of the Congo, the hierarchical UI structure proved difficult to navigate for people who have never attended formal education or are completely new to digital technology. The concept of a navigable tree structure where a sequence of decisions must be made to reach a final 'leaf node' was too abstract and therefore the navigation buttons on top of the screen could not be interpreted in a meaningful way. The participants rarely used the cancel (✖) and back button (🡐) and when they were asked about the meaning of those it became clear that they had trouble to distinguish between navigation buttons and decision tree icons.



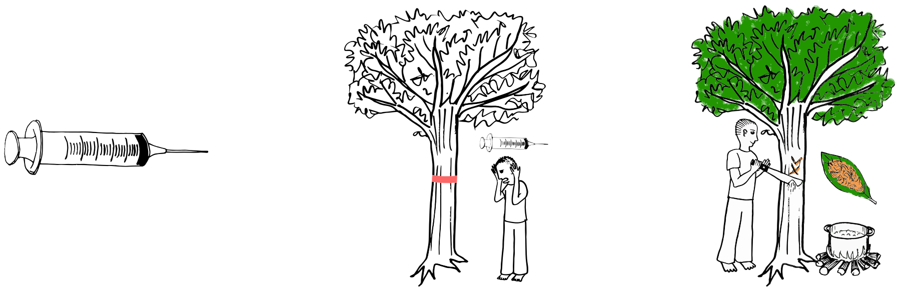
***(a)*** *Trees* ***(b)*** *Fruit trees* ***(c)*** *Myrianthus arboreus fruit*

***Figure 2.22*** *Categorical versus 'leaf' icon (icons by G. Conquest)*

The experiments further revealed that the categorisation of icons was not always logical to the participants and often there was no generic term for a category in the local language. It became apparent that Mbendjele do not have a culture of categorising things in the same ways that are common in the western world, which makes it difficult to define a categorical structure. This confirms findings of folkbiology researchers, who found that cross-cultural conceptualisations of nature tends to be misinterpreted as a lack of understanding (Medin et al., 2006; Bang et al., 2007). Medin and Atran (2004) found that native cultures with great expertise tend to reason more at more specific levels, which might explain the difficulties participants were facing in handling hierarchical UIs, starting at a very broad and conceptual category.

What adds to this problem is the challenge of designing intermediate, categorical icons versus node icons. Figure 2.22 illustrates an example of an icon sequence to tap in a hierarchical structure in order to map a specific fruit tree. Figure 2.22a represents the category 'trees', figure 2.22b represents the category 'fruit trees' and figure 2.22c refers to a specific forest tree that will be mapped. Despite the design choice to represent categories by showing multiple items, this concept was not fully understood by many of the participants (Vitos et al., 2017). During the field trials it became evident that categorical icons were often interpreted literally as opposed to its intended meaning as an 'umbrella' icon for similar items.

In general, icons were interpreted very literally. During the participatory icon design phase, locals often requested to add a forest background to icons. The researchers had not proposed this due to the fact that all icons were based in the forest. Throughout the lifespan of Sapelli and various field trips to RoC, different designs of a medicinal tree have been tested (see figure 2.23). The drawing of a syringe (see figure 2.23a), which the participants knew due to a vaccination program, was the initial attempt to present a resource used for medicinal purposes. Later, a tree was added to present the forest resource, as well as a person in pain to further illustrate the concept of healing (see figure 2.23b). The latest design, which the Mbendjele seem to prefer, is a very literal illustration of how the tree is used for turning into medicine (see figure 2.23c).



***(a)*** *Syringe* ***(b)*** *Pain* ***(c)*** *Medicinal tree*

***Figure 2.23*** *Abstract versus literal icon design (icons by J. Lewis and G. Conquest)*

In order to overcome these issues, Vitos et al. (2017) explored a different mapping technique that omits all hierarchy and on screen navigation but utilises physical objects instead. The idea was to select the object to be mapped 'in the real world' and use the digital device for geotagging and time stamping of observation as well as for its data storage and sending capabilities. Rekimoto et al. (2001) claims that building on users' knowledge by creating a link to the real world can improve participants' confidence.

The resulting prototype, named Tap & Map, consists of a smartphone app and a set of NFC cards with icons representing the objects to be mapped. In order to record a point of interest, the user needs to be in a specific location, identify the object according to a card from the stack and tap the card against the mobile phone. The pairing then triggers the app to read the GPS location and store it along with the selected card and the time stamp. In the absence of NFC cards while prototyping this idea, the concept was trialled with icons printed on paper (see figure 2.24a) and the NFC pairing was simulated. Nevertheless, it showed that the simple approach that omits all navigation achieved better results than the Sapelli interface and showed more confidence (Vitos et al., 2017). Obvious limitations of this approach is the dependency on NFC cards as extra hardware.

***(a)*** *Icon cards* ***(b)*** *Mapping process*

***Figure 2.24*** *Tap & Map experiment*

The insights gained from the scoping visit as well as user experiments of the Sapelli Collector UI informed the development of the research questions in multiple ways. Importantly it became evident that people had an interest in seeing and understanding the results of their mapping exercise. It is comprehensible that people, novice to digital technology, found it difficult to understand the relation between pressing images on a mobile phone and the concept of mapping resources. Seeing the results of the 'button pressing exercise' on a map would presumably help them understand the mapping process as a whole.

The experiments further revealed that representations were preferred to be as close to reality as possible, which encourages the use natural colour aerial or satellite images as map visualisations. While the recognition of icons was not a problem, the participants struggled with the navigational element of finding the correct screen. In order to evaluate whether digital maps can be understood, it makes sense to remove the element of navigational architecture from map understanding experiments. The use of Tap & Map revealed that, instead of going through a digital hierarchy of navigation, participants preferred the use of physical cards to input their choice, which was repliated as an information input method in this research (see section 7.3).

Further important insight gained from usability experiments of the Sapelli collector UI are the specific challenges encountered when moving HCI methods from from controlled lab situations into the rainforest. Specifically cultural differences, communication barriers as well as time constraints make it difficult to follow traditional HCI test protocols, which have to be taken into consideration for this research.

## 2.5 Research Questions

Using GIS in development work has often been dismissed as 'putting technology before people' (Jordan, 2002: p.234). It is equally argued that any technology which requires data to be taken away for analysis rather than encouraging people to undertake their own investigations limits the extent of participation and empowerment (Jordan, 2002; Haklay, 2013). While this research is in line with the previous statement, rather than concluding that technology is disempowering by nature, it evaluates whether GIS can be appropriate technology for participatory development work in areas where access to GIS is traditionally limited.

There is no universal definition of GIS, but the common denominators across literature are that GIS is a computer based system to capture, store, manipulate, analyse and visualise geographically referenced data (Worboys and Duckham, 2004; Fazal, 2008; Longley et al., 2015). While data capture is a different research topic under the umbrella of Intelligent Maps, for this research, prototypes of a portable, offline GIS were developed that allows for storage, manipulation and visualisation of data. The focus of this research lies on the challenge to provide a GIS that can be used by any user to improve understanding of local conditions and address issues that they are concerned about. Therefore, tools must be easy to use and must be adapted to each specific social and cultural environment.

The research carried out for this thesis addresses the question whether people who have an extensive knowledge of their environment but no prior exposure to cartographic visualisation or digital technology are able to understand and use digital maps. An empirical approach is applied to evaluate whether digital maps can be understood by Mbendjele hunter-gatherer communities. Importantly, it is not implied that appropriate technology will necessarily lead to a successful project, which is dependent on the implementation as well as external factors.

Building on the principles of inclusive and universal design, discussed in section 4.1.2, the participants in the experiments are people who have had no prior experience in using maps or technology and do not have a culture of reading and writing. Indigenous groups typically do not posses digital devices, but are often aware of their existence due to trade activities with village residents. By ensuring that representations are meaningful to non-literate, forest-dependent communities who have no background in using geographic visualisations, and if they can understand and successfully use and manipulate digital maps, then Participatory Geographic Information Systems and digital mapping tools, have the potential to benefit people who were previously excluded from decision making processes.

As discussed in section 2.2.4, powerful and influential stakeholders such as logging companies might have incentives to address issues of social justice and environmental sustainability but typically do not act on them. Lewis (2014) reports that companies who have been present in the Congo rainforest for several decades have little knowledge of the lifestyle and needs of local indigenous people as communication has proven to be both challenging and time-consuming and thus not considered worthwhile. Practical issues such as linguistic barriers or cultural implications of inviting indigenous representatives to formal stakeholder meetings are often in the way of active collaboration between the parties. The research carried out for this thesis investigates whether basic mapping technology can be understood and used by the communities and potentially serve as a communication tool and help overcome those barriers. The general research question answered in this thesis is:

***To what extent do non-literate hunter-gatherers in the Congo Basin understand digital maps?***

The specific focus on non-literate hunter-gatherer populations refer to the social context described in section 2.2.3. Testing map understanding with non-literate communities means that visualisations cannot make use of textual or numerical annotations. It further refers to the challenge that this context imposes on research methods. It is impossible to learn the local language through secondary sources, such as books or courses, which creates a strong dependency on translators. Moreover, it is difficult to give instructions in a standardised way, as there is no possibility to write them down in the local language. Research participants have had no or very limited exposure to formal education and are therefore new to formal test situations. On the other hand, addressing hunter-gatherer communities implies that all participants have an extensive knowledge of forest topography, which was learned solely through direct exposure. Within this context, this research attempts to answer the following questions:

*RQ 1: How can appropriate base maps be created?*
In this project, appropriate base maps (or reference maps) need to have overcome limitations of current maps as discussed in section 2.3.2. Thus, the maps are to be georeferenced and provide enough detail so that single objects (e.g. trees, huts) can be visually located. Given the context, the creation of such maps cannot rely on an internet connection and therefore must be locally processed and served. Furthermore, the creation must be affordable for non-profit organisations, such as NGOs. As will be shown in section 3.1, the most feasible solution to achieve this is to create orthophoto maps using inexpensive UAVs. To answer the Research Question, different cameras, flight parameters, georeferencing methods and processing software are tested. The results are then evaluated for feasibility, image quality, spatial accuracy, expenditure of time and processing power.

*RQ 2: Are non-literate hunter-gatherers able to understand maps?*
Map understanding is split into three sections, with each of them using empirical HCI methods to test aspects of aerial orthophotos being understood as a representation of well-known geographical landscapes. All of these experiments are conducted using culturally adapted prototypes of GIS and evaluated using an interaction log analysis. This Research Question is sub-divided into two sections answering different aspects of map understanding:

*RQ 2a: Are non-literate hunter-gatherers able read maps?*
- Can maps be understood and related to the real world as well as participants' current location?
- Can abstract symbology overlaid on a base map be understood as a location marker?

*RQ 2b: Are non-literate hunter-gatherers able contribute to maps?*
- Can marked features on a map be successfully corrected by modification of marker location or symbology?

## 2.6 Summary

Extreme Citizen Science aims to expand the traditional boundaries of Citizen Science projects by opening them up to participants of all backgrounds. This approach is applied for the Intelligent Maps project that attempts to enable local forest dependant Mbendjele communities in the Republic of the Congo to play an active role in monitoring logging activities, thereby demonstrating their claims to forest land in a context where national legislation excludes them from forest ownership and usage rights. There is an opportunity for improving inclusivity in the Congo Basin thanks to VPAs as well as the efforts of logging companies seeking FSC certification in the region. One such company, CIB, has provided opportunities for research in order to meet the requirements of social responsibility. The initial scoping trip for Intelligent Maps served as the basis to form the general Research Question of this thesis – Do non-literate hunter-gatherers in the Congo Basin understand digital maps?

In order to transfer mapping methods from the industrial parts of the world to novice users in remote areas, traditional cartography protocols need to be adapted to the specifics of the local environment. This research has identified three areas in particular, ICT's reliance on written English and internet access as well as the limitations of satellite imagery for dense forests, as the major challenges in the way of deploying technologies and approaches designed for the western world in the Congo Basin. Thus, digital mapping experiments with Mbendjele hunter-gatherer communities need to be approached accordingly. To identify existing research contributions, the following two chapters review related literature in the fields of Geographic Information Science (GISc) and Human-Computer Interaction (HCI).

# 3 Related Work in Geographic Information Science

The previous chapter introduced the context and progress made towards realising the vision of Intelligent Maps and how this research, with its focus on map understanding, fits into the bigger picture of creating a GIS that serves the needs of marginalised populations living in remote environments. The emergence of GIS has provided cartographers with new tools and methods allowing for enhancements to static maps and the introduction of multiple layering, interactivity and multimedia (Gibin et al., 2008). The advent of computer-based visualisation of geospatial data has stretched traditional cartographic domains of visual thinking and visual communication (DiBiase, 1990). More recently, the Web Mapping 2.0 era has drastically changed the landscape of internet mapping (Haklay et al., 2008). The success of 'map mash-ups' is in large parts attributable to the release of Application Programming Interfaces (APIs), which facilitate the development and implementation of mapping applications. Most importantly, APIs give access to a centralised repository of high-resolution geographic background data, including satellite data and street photography. This current trend, together with the qualitative and quantitative improvements of Earth observation products (Manakos and Lavender, 2014), has created a notion of living in an era of 'ubiquitous cartography' (Gartner et al., 2007). While satellite products have certainly contributed to addressing the 'need for maps' (Thackwell, 1969) of currently under-represented areas, they have not solved the problem. Furthermore, the complexity of GIS has constrained their use mainly to trained domain experts (Traynor and Williams, 1995; Schmid et al., 2013). The prerequisite for any kind of visualisation to be successful is for it to be accessible and comprehensible by its target audience. The lack of high-resolution maps as well as the unfamiliarity of the potential users with geographic representations and systems present challenges that are addressed in this research.

This chapter gives an overview of existing literature on map creation techniques as a prerequisite to study map understanding in remote, unmapped environments. The theoretical backgrounds of map understanding and the use of interactive mapping environments are subsequently provided.

## 3.1 Map Generation

Map-making, or cartography, has been around for several thousand years. From the imaginative circles carved onto a clay tablet in Babylon around 600 BC, it evolved into more and more intricate and accurate representations of our surroundings through the centuries. Every generation produced their own versions of maps. Claudius Ptolemy's descriptive atlas from about 150 AD in ancient Greece, instructional maps from 13th century in China, early sketches of Venetian explorers travelling the seas or ideological maps of the middle ages are a few distinct examples (Garfield, 2012). While in the 1930s, Phyllis Pearsall, the creator of the popular London A-Z maps, reputedly still had to walk more than 3000 miles to map 23,000 streets in London (Pearsall, 1990), technological advances have drastically changed the ways cartographers go about the creation of maps.

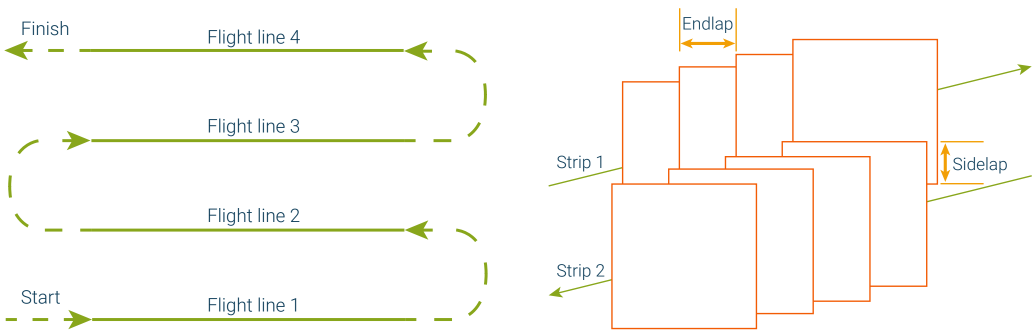
Although traditional methods such as field surveying and mapping continue to be relevant, technologies like GPS receivers have also become standard for helping to record information. Early technological innovations, such as photography and aviation, are combined in ever more scenarios advancing the field of aerial mapping. In addition, the possibility of putting sensors onto satellites orbiting planet Earth has opened up unprecedented opportunities. Whereas the field of photogrammetry has been focusing on traditional approaches with remote sensing, computer vision came up with an entirely new approach, thus advancing technology from a different angle, via maps within a game. This section reviews map making techniques from the fields of remote sensing and computer vision.

### 3.1.1 Data Acquisition through Remote Sensing

In remote sensing, data is acquired by mounting one or more sensors on an aircraft or satellite platform to record electromagnetic radiation. Active sensors, such as Radar, Lidar or Sonar, produce energy and record the backscattered amount. Passive sensors, on the other hand, measure the radiation reflected or emitted from the Earth. Laser and Radar based scanners penetrate atmospheric inferences such as clouds, due to their high level of energy. They are commonly used for 3D model generation and change detection (Jensen and Hodgson, 2004). Spectral information, that is not visible to the human eye, such as infrared and ultraviolet light, is typically used to monitor vegetation health (Gandhi et al., 2015; Reid et al., 2016), biomass (Murphy et al., 2014) or forest fires (Chowdhury and Hassan, 2015). This research deals with the creation of natural colour maps. Therefore, the following section reviews passive data acquisition methods in the range of optical wavelengths, between 390 and 700 nanometres (Rycroft, 2013).

### Traditional Aerial Photography

Paine and Kiser (2012) provide a detailed overview of aerial image acquisition and image interpretation. Aerial photography is used for projects with various dimensions, such as mapping a watershed, a county or an entire city. During the acquisition process, a camera mounted onto an aircraft records photographs of the area it flies over. Multiple flight lines are usually needed to cover a terrain in its entirety. To achieve this, the pilot has to fly back in the opposite direction after every flight line, making 180 degree turns (see figure 3.1a). This results in a succession of overlapping photographs, known as a strip. Figure 3.1b depicts a strip taken along a single flight line. An intervalometer is used to set the time between individual exposures along a flight line. To do so, the aircraft's speed and the scale of the desired images must be considered so that the aerial photograph overlaps the next photograph in the flight line. This is essential for producing at least two to three photographic views of each object to be mapped along a flight line. For the best results, an overlap of approximately 60 percent is required. This is referred to as an endlap, while the overlap of two flight lines is called a sidelap. The sidelap is usually between 20 to 30 percent. Values can change depending on the specifics of an area. In very mountainous terrains, for example, an overlap of more than 80 percent produce the best shots (Jensen, 2000; Paine and Kiser, 2012).




***(a)*** *Flight line pattern* ***(b)*** *Photographic overlap*

***Figure 3.1*** *Aerial photo acquisition (Paine and Kiser, 2012)*

### Satellite Imagery

In 1957, the launch of the first man-made satellite, Sputnik 1, by the Soviet Union established an 'open skies' policy. The CIA and the United States Air Force began operations for the secret Corona orbital satellite reconnaissance program in 1959, aiming to securely gather photographic information from enemy territories during the Cold War. After eight failed missions that did not produce any imagery, the ninth mission, Mission 9009, was a success (McDonald, 1997b). It resulted in more coverage of the Soviet Union than all of the previous missions combined (Ruffner, 3 1995; Jensen, 2000). In a revolutionary manner, the satellite ejected a canister containing the reconnaissance film, which was caught mid-air by specially equipped aircrafts (Gibson and Power, 2013). Since then, satellite technology has improved considerably, and as with many technologies that were initially invented and advanced for military purposes, satellites too became available for civilian use (EC-EDA-ESA-CSG, 2010).

Table 3.1 provides an overview of the major, currently operating Earth Observation satellites (as of 2017). All shown satellites have bands in the wavelengths ranges of red, green and blue, allowing for the generation of true-colour orthophotos. The three satellites operated by the NASA or the ESA are open data, meaning that it is free to download processed and georectified orthophotos as well as use them for any purpose. They are at the same time the satellites with the lowest spatial resolution. The data refers to ground sampling at nadir for multi-spectral sensors. The costs indicate an order of magnitude and can vary depending on various factors, such as extent or distribution rights (World Bank Group, 2016b).

***Table 3.1*** *Currently operating Earth Observation satellites (World Bank Group, 2016b)*

| Satellite | Open Data | Spatial Resolution (m) | Revisit Rate (days) | Cost ($ per km$^2$) |
|---|---|---|---|---|
| Airbus Pléiades | No | 2 | 1 | 13 |
| Airbus SPOT 6/7 | No | 6 | 1 | 5.15 |
| Blackbridge RapidEye | No | 6.5 | 5.5 | 1.28 |
| DigitalGlobe WV2 | No | 1.8 | 1.1 | 17.5 |
| DigitalGlobe WV3 | No | 1.24 | 1 | 32 |
| EU Sentinel 2 | Yes | 10 | 5 | 0 |
| NASA MODIS | Yes | 500 | 1.5 | 0 |
| NASA/USGS LandSat 7-8 | Yes | 30 | 18 | 0 |
| UrtheCast Deimos-2 | No | 5 | 2 | n/a |
| UrtheCast Theia | No | 5 | 15 | n/a |

The advent of satellite imagery has without a doubt opened up new possibilities and Broich et al. (2011) report that most conservation researchers and practitioners currently rely on satellite-based remote sensing for mapping and monitoring land use change. Wilbanks (2004), however, warns that there is a danger of technology shaping research agendas. Specifically, there is an imbalance of attention to different research issues due to the amount of effort required to collect information as a basis for analysis and discourse (Wilbanks, 2004). An alternative to purchasing existing products is to acquire or commission the acquisition of data tailored to specific project requirements.

**UAV Imagery**

Aerial or satellite imagery is often inaccessible to researchers due to financial constraints or specific quality requirements, such as spatial or temporal resolution (Koh and Wich, 2012). In the last decade, drones, or Unmanned Aerial Vehicles (UAVs), as they will be called in the remainder of this thesis, have become a game changer in the field of Earth Observation. Unmanned aircrafts are by no means a new technology as they have been around as long as powered flights. Until the last decade, however, UAVs were mostly used either by the military or by hobby pilots that are flying for the fun of it (Kakaes et al., 2015). The change was brought about by precision improvements in GPS positioning as well as technological advancements and price drops in accelerometers and digital cameras. Various UAV types have been classified according to criteria, such as size, flight range, altitude and endurance (Everaerts et al., 2008; Hardin and Hardin, 2010; Paneque-Gálvez et al., 2014). This section refers to battery powered, small-scale UAVs with light payloads, able to fly short missions up to an hour at altitudes up to 200 metres. These small-scale UAVs are typically used for environmental mapping and monitoring due to their light weight and high manoeuvrability. Besides, they are often equipped with 360 degree gimbals, offering ideal conditions for aerial photography (Kakaes et al., 2015).

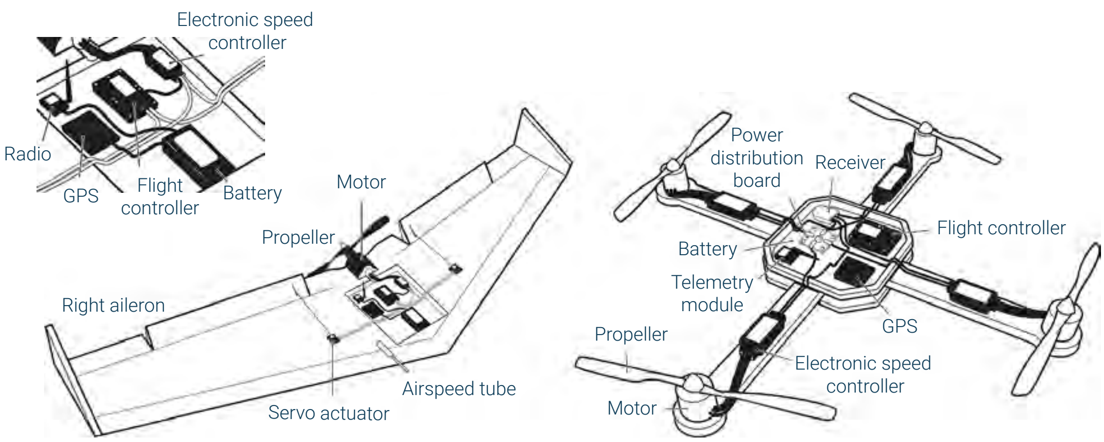



***Figure 3.2*** *Fixed-wing system (left), multi-rotor system (right) (Kakaes et al., 2015)*

Within the category of small-scale UAVs, fixed-wing or multi-rotor aircrafts are distinguished (see figure 3.2). The trade-off between both systems is that of endurance versus manoeuvrability. Fixed-wing UAVs are typically lightweight, fast and can fly for up to one hour due to their gliding characteristics. On the downside, they cannot hover or move in a vertical direction. Fixed-wing pilots need to be more skilled and clearings need to be bigger for starting and landing. Multi-rotor aircrafts are easier to control, but require a lot of energy, resulting in much shorter flight times. Hybrid models, that combine features of both systems, are in development (Theys and De Schutter, 2016). For now, there is no hybrid model in market production, due the the technical difficulty of switching between the states of hovering and gliding (Kakaes et al., 2015).

At present, the most popular models are the quadcopters of the DJI Phantom series, due to their low price and ease of use (Kakaes et al., 2015). Sophisticated electronics allow for individual speed regulation of each propeller, which guarantees high stability and manoeuvrability. Additional rotors add stability as well as the capability to carry more weight at the cost of flight time.

Besides the affordability, there are a number of advantages that UAVs have compared to traditional image acquisition methods. When flown at low altitudes, consumer grade digital cameras can achieve image resolutions of one pixel corresponding to few centimetres on the ground. At this resolution, individual trees can be identified as well as gaps in forest canopy (Paneque-Gálvez et al., 2014). Operational costs are minimal, which makes it possible to frequently update a set of images and detect change over time. Many UAVs are equipped with sophisticated flight planning and autopilot software that allow for pre-programmed, autonomous flights. Previously inaccessible areas, such as steep terrains or swamps, can be explored and moreover, small-scale drones are easily manoeuvrable and therefore suitable for acquiring images from different vantage points and angles. These allow for three-dimensional scene recreation and the generation of Digital Surface Models (DSMs) (Haarbrink and Eisenbeiss, 2008; Udin et al., 2012). As opposed to satellite imagery, scenes captured by UAVs are not affected by cloud cover, and ownership rights are with the image creator, meaning that the data can be reproduced and shared in any format.

On the downside, small-scale UAVs have very limited flight times as well as payload due to high energy requirements. Despite cloud cover not being an issue, it is impossible to fly a small-scale UAV in atmospheric conditions like heavy winds and rain. Even in good weather, there is always the risk of collision caused by either technical or human error. Safety is an issue on various levels. Despite the danger of damage or injury through crashes, people can put themselves at risk when monitoring criminal activities, such as wildlife poaching or illegal logging activities. Even when not observing criminal activities, prior and informed consent is always required if there is a chance of people being captured on camera. With the popularity of drones being used for civilian purposes, people are concerned about unethical use and possible privacy violations. Official laws for the use of civilian UAVs vary from country to country (Stöcker et al., 2017).

Legislation has difficulty keeping up with the rapid spread of UAV technology (van Wegen and Stumpf, 2016). The lack of regulations regarding their usage also poses a barrier to research and innovation (Watts et al., 2012). UAV traffic management systems, user certification and preservation of privacy are an ongoing concern in Europe. The European Aviation Safety Agency (EASA) is holding a consultation on proposed unmanned aircraft system regulation at the time of writing. Under these regulations, whether the UAV flight is commercial or non-commercial in nature is not of concern. Instead, permissions are linked to a UAV's assigned risk factor, which is determined based on the vehicle's technical specifications. Small UAVs under 25 kilograms that fly below 120 metres, as used in this research, are categorised as low risk and therefore do not need special permissions (EASA, 2017).

Stöcker et al. (2017) compiled and published a global overview of drone regulations for civil applications, as shown in figure 3.3. One-third of all countries have regulations in place and just over half of all countries do not provide any legal framework regarding the use of civil UAVs. 7.69% of all countries announced that they have UAV regulations pending amongst which some of them, such as Kenya, have already published draft regulations. In Egypt, Uzbekistan and Cuba, the use of UAVs is officially prohibited. Many countries do not yet have any regulations in place, but it can still be difficult to get permission to fly due to authorities being suspicious about the purpose and use of the device and captured data.

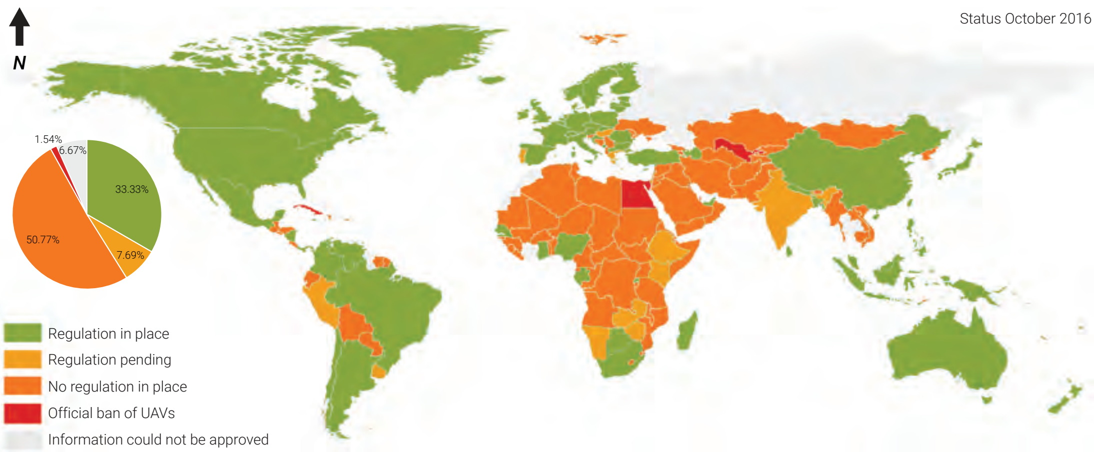



***Figure 3.3*** *Global overview of UAV regulations after Stöcker et al. (2017)*

While some people have potentially legitimate concerns about ethics and safety issues of these new technologies, other people have become part of the movement. The price drop of UAVs has brought powerful mapping tools in the reach of amateurs and decentralised the previously strictly professional field of aerial photogrammetry. Scientists and hobbyists alike are flying and even building their own unmanned aircrafts (Koh and Wich, 2012). With more than 80,000 members, DIY Drones (Anderson, 2016) has become a thriving open-source community of people creating and sharing hard- and software solutions with the result that home-made UAVs have long outnumbered military drones (Anderson, 2012). MacLennan (2014) from Digital Democracy has built a fixed-wing UAV together with the Wapichana community in Guyana. This way they learned how to to build, fix and operate a drone for the purpose of monitoring illegal logging activities.

### 3.1.2 Orthophoto Generation

Following the acquisition of images, several processing steps are required to generate georeferenced orthophotos. Orthophotos have the quality to be planimetrically correct, thus, they allow for accurate distance, area and direction measurements (Paine and Kiser, 2012). In the case of multi-spectral sensors, red, green and blue bands are combined to achieve a true colour appearance (Sreenivas and Chary, 2011). Raw satellite imagery, as received at a ground station, as well as aerial photographs are subject to distortion (e.g. image motion, lens distortion) and displacement (e.g. Earth curvature, platform tilt, relief displacement) (Toutin, 2003; Paine and Kiser, 2012). Most of these parameters can be modelled and removed mathematically. Relief displacement typically causes artefacts in high-resolution orthophotos. An analysis of methodologies for 'true' orthophoto generation has been provided by Bang et al. (2007). Roll, pitch and yaw effects of aerial platforms can be rectified if the amount and direction of the tilt is known (Paine and Kiser, 2012). Satellite systems are geometrically quite steady, making geometric rectification a simple transformation process. The geometry is corrected using Ground Control Points (GCPs), with known image coordinates as well as reference coordinates (Kim and Im, 2003; Sreenivas and Chary, 2011). The geometric transformation can be automated without the need of GCPs if one or more georeferenced images of the same scene are available (Zitova and Flusser, 2003). Finally, pixel values are rearranged, known as re-sampling, to match the grid of the new reference coordinate system (Kim and Im, 2003).

Photogrammetry is a long established field in the geosciences and orthophotos have been created from aerial images as early as the 1960s (Smith, 1995). The traditional approaches outlined above work well with near-parallel stereo-pairs of images that have a high overlap, given that the camera's external calibration parameters (camera projection centre and rotation matrix) and internal calibration parameters (focal length and lens distortion) are known at the time of image acquisition (Verhoeven et al., 2012). These limitations restrict orthophoto generation to trained professionals with access to the expensive equipment. An alternative approach for surface reconstruction from two-dimensional images is called Structure from Motion (SfM) (Ullman, 1979) and comes from the field of Computer Vision. There is no need to use calibrated cameras during image acquisition (Quan, 2010), which makes the approach well suited for a wide user range with consumer rate cameras and UAVs.

As opposed to traditional photogrammetry, SfM computes the camera positions and orientations through feature matching algorithms applied to a set of overlapping images. Once the camera parameters are known, the scene is reconstructed through the method of triangulation shown in figure 3.4.

If 2D image coordinates $(x_{a_1}, y_{a_1}, x_{a_2}, y_{a_2})$, 3D projection centre coordinates $(X_{O_1}, Y_{O_1}, Z_{O_1}, X_{O_2}, Y_{O_2}, Z_{O_2})$ and orientation $(\omega_1, \varphi_1, \kappa_1, \omega_2, \varphi_2, \kappa_2)$ are known, the three-dimensional point (a) can be determined through the creation of triangles. The major advantages of the SfM workflow are the cheap hardware and software requirements compared to traditional photogrammetry as well as the achievable spatial resolution, which is comparable to modern terrestrial laser scanners (Carrivick et al., 2016).

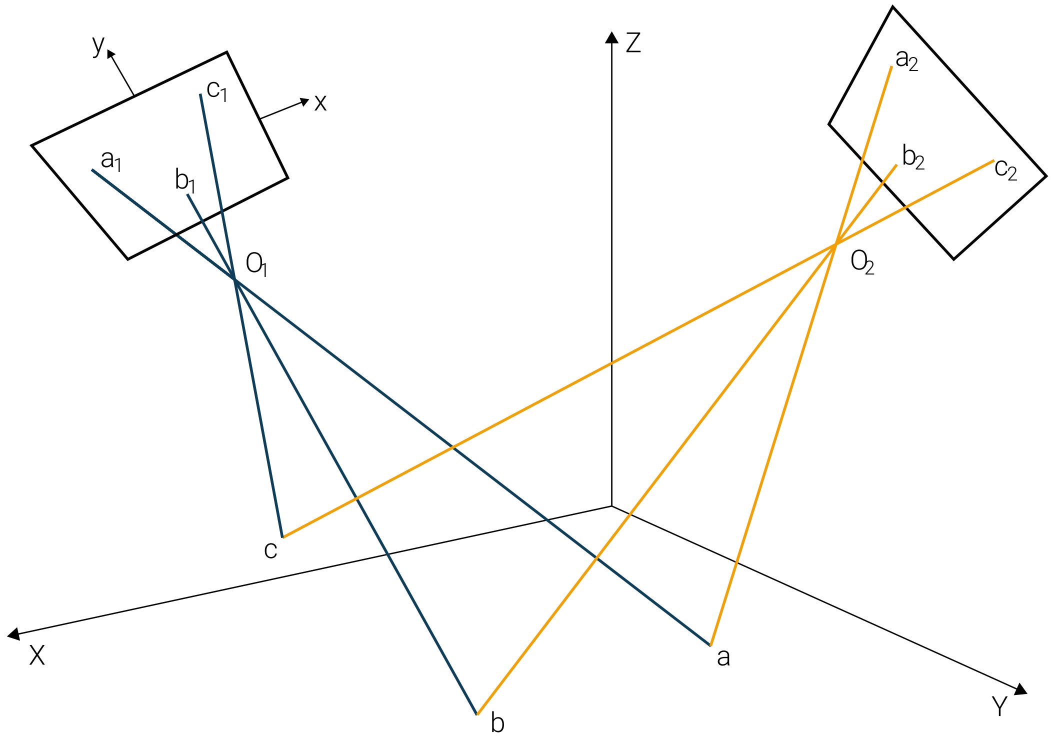



***Figure 3.4*** *Reconstruction of 3D points from 2D images (Kanatani et al., 2016)*

This section provides a detailed overview of state-of-the art techniques to generate orthophotos from images captured by uncalibrated airborne cameras. It serves as a theoretical background to answer research question 1: *How can appropriate base maps be created?*. Figure 3.5 illustrates a typical SfM pipeline, which is divided into four major parts, Image Matching, 3D Reconstruction, Georeferencing and DSM & Orthophoto Generation. Each of these steps contains one or more techniques that are described in the section below. Popular algorithms or implementations are optionally added in brackets. Chapter 6, which addresses research question 1, refers back to these techniques by evaluating the suitability of the SfM pipeline and different implementations thereof in the context of this research.

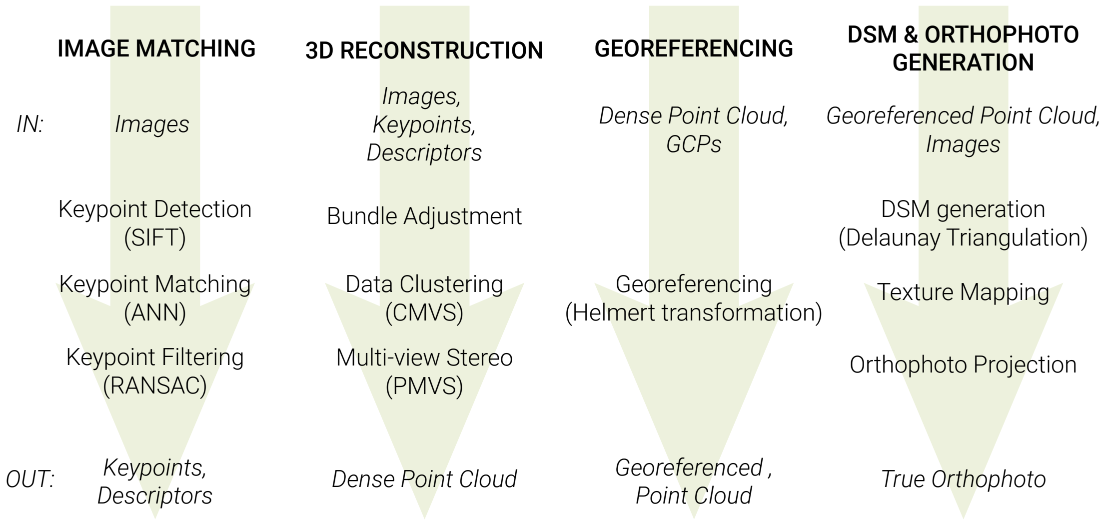



***Figure 3.5*** *Orthophoto generation pipeline*

**Keypoint Detection**

The first step in the SfM process is the identification of common points on multiple photographs taken from varying positions and angles. The quality of the reconstructed 3D model and final orthophoto heavily depends on the result of the feature detection stage. Amongst the varying approaches for image registration (Lucas et al., 1981; Harris and Stephens, 1988), so-called wide baseline matching techniques proved to be most adequate for feature identification between images taken from widely different views (Snavely et al., 2008). In a comparison study, Mikolajczyk and Schmid (2005) identified the Scale-Invariant Feature Transform (SIFT) feature recognition system (Lowe, 1999) to be most robust against changes in viewpoint and scale, which is the most commonly implemented solution today (Carrivick et al., 2016). The SIFT approach, as detailed in Lowe (2004), automatically identifies 'keypoints' in each image, independent of scale and location. Consequently keypoint descriptors are created, which transform image gradients into representations that are sufficiently distinctive but largely insensitive to shape distortion and variations in illumination.

**Keypoint Matching**

Following the keypoint identification and descriptor assignment, the keypoints need to be matched across multiple images in order to reconstruct a 3D scene at a later stage. The algorithm for Approximate Nearest Neighbour Searching after Arya et al. (1994) is commonly preferred over the brute force Nearest Neighbour algorithm due to its substantially reduced runtime in multidimensional space (Carrivick et al., 2016). Furthermore, Lowe (2004) suggests to limit testing to the first 200 nearest neighbours, which reveal 95% of correct matches. To achieve even greater confidence, the matched keypoints are filtered using a Random Sample Consensus (RANSAC) algorithm (Fischler and Bolles, 1981), which separates 'inliers' from 'outliers' in a given dataset. The fast, accurate and robust (Choi et al., 2009) sampling process is iteratively run on different subsets until a 95% chance is reached that a subset only contains inliers. If the minimum requirement of two keypoints and three images are met, the inliers are used to build 'tracks', which link keypoints in a set of images. Otherwise, keypoints are automatically discarded (Snavely et al., 2008). This method also ensures that moving features, such as people crossing the scene, are removed from the dataset due to their varying position relative to other keypoints (Westoby et al., 2012).

**3D Reconstruction through Bundle Adjustment**

Bundle adjustment is the actual 'structure-from-motion' (Ullman, 1979) computation, despite the term being commonly used to refer to the entire described process chain. Thus, SfM refers to the sparse point cloud (structure), which is generated at the same time as camera positions (motion) are estimated (Carrivick et al., 2016). Bundle adjustment, which originated in the field of photogrammetry (Brown, 1958; Slama et al., 1980), refers to a 'bundle' of light rays connecting projection centres to 3D points while minimising the reprojection errors through 'adjustment' (Szeliski, 2010). An extensive review of the theory and methods of bundle adjustment has been carried out by Triggs et al. (2000). The principle is to use triangulation in order to estimate 3D point positions incrementally, thereby reconstructing the geometry of the scene using a relative coordinate system. To improve the accuracy of the solution, Szeliski (2010) suggest, to still perform a full bundle adjustment over all camera frames. The result of bundle adjustment is a 'sparse' point cloud which is typically enhanced to a much denser point cloud using Multi-View Stereo (MVS) techniques (Seitz et al., 2006; Furukawa and Ponce, 2007). When dealing with large datasets, Random Access Memory (RAM) requirements can be immense while carrying out MVS computations. To increase memory efficiency, Furukawa et al. (2010) developed a Clustering Views for Multi-View Stereo (CMVS) technique that splits the data into clusters of overlapping images that are processed separately. Seitz et al. (2006) categorise common MVS algorithms into four classes, which Carrivick et al. (2016) name voxel-based methods, surface evolution-based methods, depth-map merging methods and patch-based methods. A well-performing (Ahmadabadian et al., 2013) and widely used algorithm is the Patch-based Multi-View Stereo (PMVS) after Furukawa et al. (2010).

**Georeferencing**

Despite the ability to reconstruct relative camera positions and 3D point clouds through bundle adjustment, it is impossible to infer absolute locations and distances with this method. The transformation from an arbitrary model space into a real world geographic coordinate system, such as Universal Transverse Mercator (UTM) can be achieved through direct or manual georeferencing (Turner et al., 2012). The first approach requires geotagged photographs with approximate GPS coordinates. Along with the camera frames from the bundle adjustment, these are used to carry out a seven-parameter Helmert transformation (Deakin, 1998). Despite its simplicity, direct georeferencing is the least accurate method when utilising low-cost and uncalibrated consumer rate cameras (Harwin and Lucieer, 2012). Higher accuracies can be achieved when the Helmert Transformation is based on a minimum of three, manually added, GCPs. Commonly, a hybrid approach is used, where direct georeferencing provides approximate locations for the initialisation of bundle adjustment and then GCPs are added for absolute positioning (Ryan et al., 2015; Carrivick et al., 2016).

Acquiring GCPs in a previously unmapped territory, in absence of specialised photogrammetry equipment, requires the use of consumer grade GPS receivers. The majority of today's mobile phones as well as many other devices are equipped with various embedded sensors, such as a GPS receiver, to allow for efficient collection of location data. Borriello et al. (2005) claim that GPS is truly ubiquitous due to 24 slot arrangement (figure 3.6), which ensures that there are a minimum of four satellites in view on any point on Earth. Since February 2016, there have been a total of 31 operational GPS satellites in orbit (US Government, 2017) as well as 24 of Russia's GLONASS satellite system. Devices can increasingly access these in addition to GPS satellites. Nonetheless, there are limitations in practice. At least four satellites are required to determine latitude and longitude. Additional satellites add information such as altitude and improve the location's accuracy (Milette and Stroud, 2012). Despite the five to ten satellites that are typically in visible range (Küpper, 2005), the radio signal emitted by the satellites might have difficulties to penetrate dense vegetation, which makes it difficult to get accurate position fixes in places like tropical rainforests (Borriello et al., 2005).

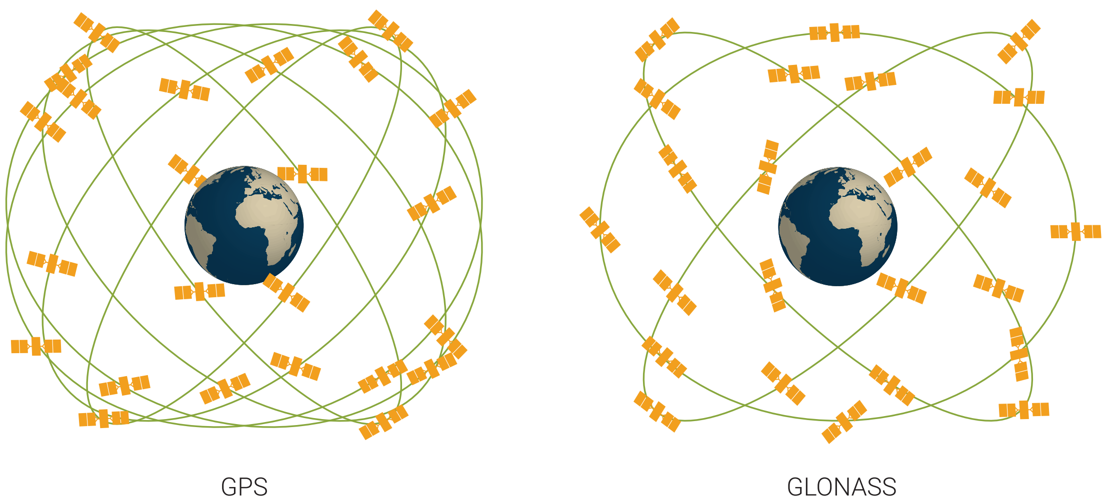



***Figure 3.6*** *Satellite constellations*

There are two classes of errors that affect the quality of a GPS location fix: User Equivalent Range Error (UERE) and Dilution of Precision (DoP). The former represents the error budget caused by several sources: ionospheric and tropospheric delays, measurement noise, ephemeris and clock error, multipath offset and selective availability. DoP indicates the geometry of the satellite constellation, where bigger angles between the satellites result in higher accuracies for the derived location fix and vice versa (figure 3.7).

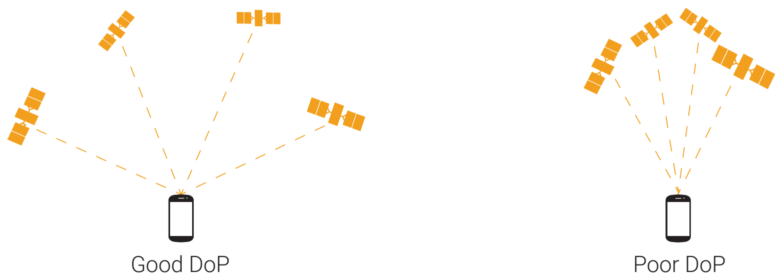


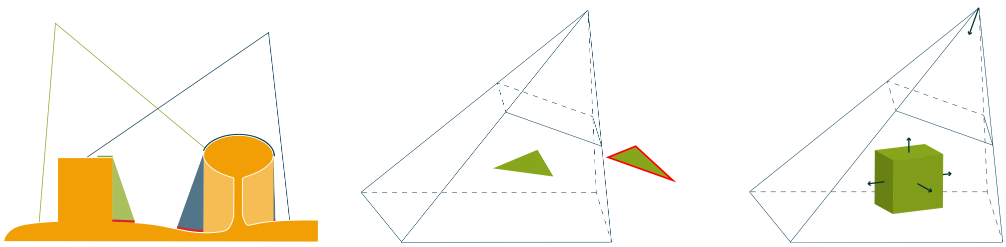

***Figure 3.7*** *Dilution of Precision*

Under good conditions and without any correction, autonomous GPS can achieve a horizontal positional error in the order of a few metres. This will vary with receiver types and specific testing conditions. For example, Wing et al. (2005) tested six different consumer grade units. Performance was found to vary considerably among units and was strongly influenced by canopy cover. Positional accuracy of the best performing units varied between one and five metres (average error) under open sky conditions (Zandbergen and Barbeau, 2011). In addition to position and time, a GPS receiver typically estimates the accuracy of a position fix. This accuracy denotes how close the fix is to the correct, but unknown, position (Küpper, 2005). Basic algorithms for estimating the accuracy are described in textbooks such as Kaplan and Hegarty (2005), but receivers generally use proprietary algorithms that take into account information about the errors mentioned above (Kjærgaard and Weckemann, 2010).

**DSM & Orthophoto Generation**

The next step on the way to orthophoto generation is to create a DSM. Typically, a Delaunay Triangulation (Tsai, 1993) is applied to the dense point cloud, resulting in a consistent polygonal model called Triangular Irregular Network (TIN) or 'mesh'. Starting with a single equilateral triangle that covers the full extent of the point cloud, points are added one by one and new triangles are created based on the rule that no vertex lies within any of the circumcircles of the triangles in the mesh. After the triangulation is finished, the segments of the initial triangle are removed, resulting in a TIN representation of the scene structure.

The final step, in which the source imagery, the camera orientation parameters and the DSM are used to generate an orthophoto, is typically carried out in two steps: texture mapping and re-projection of images (Barazzetti et al., 2014). An automated approach for texture mapping is detailed in Previtali et al. (2012). The procedure is split into a geometric part (visibility analysis, texture assignment) and radiometric part (colour adjustment). Traditionally orthophotos have been created using differential rectification (Bang et al., 2007) based on Digital Elevation Models (DEMs), ignoring tree or building heights. In high-resolution imagery, this often resulted in significant distortions (Sheng et al., 2003; Deng et al., 2015). A 'true' orthophoto has the quality that all points visible on the surface are in their correct planimetric position (Karras et al., 2007). To eliminate the effect of geometrical displacement, areas of occlusion need to be detected during the visibility analysis. In this, each triangle of the TIN is re-projected onto the image space, checking whether its visibility is impaired by intersecting another triangle.



***(a)*** *Occlusion detection* ***(b)*** *View Frustum Culling* ***(c)*** *Back-face Culling*

***Figure 3.8*** *Performance enhancement for occlusion detection*

Figure 3.8a illustrates occluded areas in red. In order to reduce the computational complexity of checking each triangle for visibility, View Frustum Culling and Back-face Culling can be applied. View Frustum Culling (figure 3.8b) automatically excludes all triangles outside the View Frustum and Back-face Culling (figure 3.8c) labels those triangles as occluded that have a normal vector bigger than 90 degrees from the camera orientation and are therefore not visible in the photo. Previtali et al. (2012) additionally found that it is enough to limit the intersection tests to the nearest neighbours of the reference triangle, with the number depending on quality of the model and image scale. Once, the visible triangles are known, texture sources are chosen based on quality parameters such as image resolution and camera viewing direction.

When multiple aerial images are used to texture a DSM, radiometric variations exist due to varying reflection angles between sun, surface and the camera. This commonly results in obvious seam lines when mosaicking the images. Tian et al. (2016) compare the performance of five different seam elimination algorithms concluding that the Wallis dodging and Gaussian distance weight enhancement method is time-efficient while producing good results. Wallis dodging (Sun and Zhang, 2008) is used to adjust the brightness of matched images. Gaussian distance weight distribution fuses overlap regions of images by smoothing artefacts of dislocation across the overlap region using a Gaussian kernel function. Finally, starting from the textured digital model the orthophoto is obtained by projecting the model texture onto the defined projection plane.

## 3.2 Map Understanding

In the past, geographers have often described cartography as graphic communication. The communication model was developed by Board (1967), and later adapted and promoted by Koláčný (1969) with the effect that communication came to be seen as the primary function of cartography, with the map being the vehicle. While the various models vary in their details, they all share a basic framework (figure 3.9), where an information source is accessed by a cartographer who determines what information will be depicted and how. At the centre of the process is usually a map (or another cartographic representation), and a user who 'reads' the map and develops some understanding of it by relating the map information to prior knowledge.

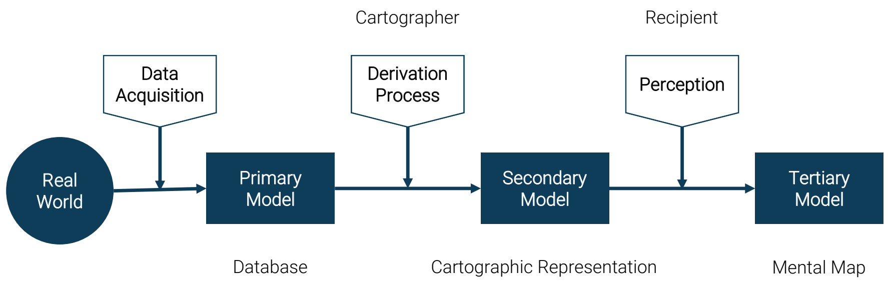



***Figure 3.9*** *Cartographic communication (MacEachren, 2004; Persson et al., 2006)*

According to the communication model, maps are reviewed on a functional basis, where function is defined as the communication of a predetermined message. However, MacEachren (2004) states that most maps clearly have a function, but they are rarely produced to communicate a specific message. Information that a pupil extracts from a map, for instance, is determined by the question the teacher asks. An analyst in a research project might produce a map at an early stage in order to explore spatially distributed phenomena. Today it is prevailingly believed that, instead of receiving a specific message, the user constructs information from spatial representations provided by the map producer. Instead of treating the cartographer and the maps as a network through which information is filtered, perceptual and cognitive processes involved in both map reading and spatial information processing are studied (MacEachren, 2004; Lobben et al., 2015).

### 3.2.1 Map Reading

To be able to interact with the world, humans have the ability to learn, remember and utilise information about the spatial arrangement of their environments (Shelton and Pippitt, 2007). This information can be learned in different ways. Two common ways for humans to familiarise themselves with environments are exploratory navigation and map reading (Moeser, 1988; Darken and Peterson, 2001). Neurological studies show that the same regions in the brain are activated when directly experiencing an environment and when using geospatial images (Maguire et al., 1998; Lobben et al., 2009).

When people are asked to point in the direction of the Eiffel Tower, for example, and they are then asked to point at the nearest supermarket, it is likely that they use two different types of spatial knowledge. For the first task, people usually use a mental image of Europe (or France, depending on the present location) and estimate their current orientation to compute the direction of the Eiffel Tower. For the second task, people estimate the location based on route knowledge from their current location to the chosen supermarket (Thorndyke and Hayes-Roth, 1982). Looking at the Earth from above reveals spatial information, such as shapes of landmasses, which are almost impossible to perceive directly through navigation. The utilisation of maps allow people to go beyond their direct experience of the environment and think systematically about spatial relations between places (Liben and Downs, 1993; Wood, 1992).

A cartographic visualisation is not simply an instrument for communication, but also a tool for acquiring spatial understanding and knowledge (Jones et al., 2009). Reading a map requires the reader to understand the correspondences between the map and the space that it describes. There are two fundamental types of correspondences between map and space: identity, and relational correspondence. Identity correspondence means that individual map elements represent real world features. Relational correspondence means that both the map elements and the corresponding features also relate spatially to each other. Information shown on a map is typically depicted from above at a vastly reduced scale (Presson, 1982).

To investigate whether this mental transformation process is an innate human ability, numerous studies have been carried out with young children. Bluestein and Acredolo (1979) and Blaut et al. (2003) show that pre-school children can establish the basic correspondences between map and space and are able to interpret the depicted symbols in order to locate a hidden target, if the map and the space are physically aligned. In their study, about half of the 3-year-olds, most of the 4-year-olds, and all of the 5-year-olds were able to find the target under these conditions. To investigate how children understand the symbolic information shown on a map, further research has been carried out where the map and the space were not physically aligned, which adds a further cognitive step to the process. Only the 5-year-olds were able to find the target when the children were presented with maps that were rotated 180 degrees relative to the room.

Remington and Williams (1986) and Shurtleff and Geiselman (1986) show that it is easier to learn and remember maps when their features are illustrated in forms that are familiar to the reader, or when the arrangement of features is geographically logical as opposed to random. These results indicate that the more 'real' a stimulus is, the more likely it is that viewers will link it to their general knowledge of maps (Ormrod et al., 1988; Kulhavy and Stock, 1996). Ormrod et al. (1988) evaluated map learning in regards to the readers' prior knowledge on principles of geographic arrangements. They argue that a map is not a random layout of features but follows patterns that exist in both natural and man made structures. Their study shows that people can easier encode a map in memory if they are familiar with the depicted spatial relationships. These findings suggest that hunter-gatherers who have never seen a map of familiar space before are likely to be able to interpret it without the need to actively learn it.

### 3.2.2 Visual Realism

In the early 1950s, a few years before the first earth observation satellite was launched, the artist Hal Shelton created a series of natural colour maps. He believed that the conventional map symbology typically used for topographic maps was too specialised, and therefore difficult for general audiences to understand. He advised against the use of abstract concepts, such as lines, since they rarely appear in nature. The familiarity of the depicted landscapes on natural colour maps would make them more accessible to diverse audiences (Patterson and Kelso, 2004). Visual realism in geospatial images significantly affects the cognitive processing of the viewer. Low visual realism demands interpretation of abstract symbology in the image, but at the same time directs the viewer's attention to essential features (Berendt et al., 1998). On the other hand, high visual realism is easy to interpret but requires extraction of the relevant features (Kettunen et al., 2014). Shelton's initial concern that the usage of too many colours may overwhelm the user did not materialise. Although it is nearly impossible to create a meaningful legend explaining the various colours contained in photo-realistic maps, Shelton claimed that the need for the presence of legends on a map, as well as text labels, are evidence of a map's failure to communicate and are the result of poor design (Patterson and Kelso, 2004). Undeniably, the creation of natural colour maps at that time required a vast amount of artistic skill and manual work. Figure 3.10 shows a map of Italy drawn by Shelton next to an image taken by NASA's MODIS satellite.

***(a)*** *Natural Colour map by Hal Shelton, ca. 1968* ***(b)*** *NASA MODIS satellite image taken in 2003*

***Figure 3.10*** *Natural colour images (Patterson and Kelso, 2004)*

The satellites Ikonos and Quickbird, launched in 1999 and 2001, were the first to produce data for commercial use with a spatial resolution of a few metres or less. Simultaneously, high performance graphics cards became the norm for standard desktop computers due to the demands of the gaming community. These technological advances, together with broadband internet access, paved the way for virtual globes to become a reality for personal desktop computers. Even before the named satellites were launched, in 1998, former US vice president Al Gore said in a visionary speech: "I believe we need a 'Digital Earth'. A multi-resolution, three-dimensional representation of the planet, into which we can embed vast quantities of georeferenced data" (Gore, 1998). Although other companies released their virtual globe applications earlier (e.g. NASA World Wind), it was Google Earth, launched in 2005, that attracted world-wide attention (Bailey and Chen, 2011). In the same year, Allen Carroll, chief cartographer at the National Geographic Society in Washington DC, shared his idea that a tool like Google Earth would inspire people and have a positive impact on their perception of the natural environment: "The ability to zoom from the whole planet down to the home and backyard will help people make the connection between themselves and their planet [...] Google Earth will no doubt raise awareness about how small and precious our Earth is" (Biever, 2005).

Google Earth was downloaded more than 500 million times in less than five years after its release (Bailey and Chen, 2011), not least due to its ease of use and comprehension. Human memory retention improves for images comprised of natural colours compared with false colours or black and white (Wichmann et al., 2002). Furthermore, the human brain (and to some extent image processing systems) can extract meanings by identifying known features such as trees, mountains, lakes and buildings (Goodchild, 2008). Blades et al. (1998) have carried out several studies to show that nearly all humans, in all cultures, acquire the ability to read and use map-like models, such as aerial and satellite photographs, in very early childhood. Two of the reported studies were carried out in Iran and Mexico, where it was not feasible to obtain local aerial images at the time. Instead the children were shown an aerial photograph of Sheffield, England. The results show that the concept of the map was understood, but does not give further indication as to whether they could relate the maps to a known environment.

While all maps are fundamentally abstractions of the real world (Patterson, 2002), different types of maps convey different views of the Earth's surface. Topographic and vector maps provide structured views of previously selected information according to what was deemed important by the cartographer. Such non-photorealistic representations enable map makers to portray visual information in a purpose and task oriented way (Döllner, 2008). Aerial and satellite images, on the other hand, present the real world's properties based on physical visibility and technological capabilities. It is regarded as a more objective view of the world as the classification of information is entirely left to the map user (Bianchin, 2007). It is commonly argued that photorealistic representations are preferred by users but tend to be less effective at aiding task performance (Hegarty et al., 2009; Hegarty, 2013; Wilkening and Fabrikant, 2011). On the other hand, Hile et al. (2009) used aerial orthophotos in their experiment and appraised them as advantageous for route planning and navigation. Svatonova and Rybansky's (2014) study of interpreting aerial images carried out with teenagers in different age groups showed that younger pupils of eleven years performed better at drawing the shortest route task on satellite imagery than on topographic maps, while 15 and 19 year old pupils achieved slightly better scores on topographic maps.

Wardlaw (2010) states that aerial photographs, in combination with intuitive pan and zoom controls, are more accessible to lay users than topographic maps. Drachal and Debowska (2013) believe that images of the Earth's surface should be increasingly used as teaching material for geography at all levels. Despite the popularity of natural colour images of the Earth's surface, Patterson and Kelso (2004) point out that satellite images are rarely used as raster base maps. In the cartographic domain, they are mostly used to create and update topographic maps (Orford, 2008), and they are sometimes used as stand-alone thematic insets or decorative introductory pages in atlases. Patterson and Kelso (2004) reason that natural colour maps are not appropriate as backdrop layers, as their high complexity detracts attention from the information represented on the map. Furthermore they believe that overlaying natural colour maps with coloured polygons should be avoided. Other reasons given for avoiding the use of satellite imagery as base layers include: meteorological interference, inappropriate colour variations, and relief inversion.

Map legibility may become problematic when hues, colour lightness levels or shapes of the symbology match the background too closely. Raposo and Brewer (2013a) describe strategies to avoid this through the use of simultaneous contrast, strategic hue and lightness selection, multi-band text halos, transparency, strategic sequencing of layers, and use of classical elements such as road casings. Raposo and Brewer (2013b) come to the conclusion that map readability is more affected by location than by design. Goodchild (2008) points out the patchwork character of current global satellite datasets, which stems from variations in the age of the imagery as well as the time of the year the photos were taken. Despite these limitations, the Google API is increasingly used to visualise data on top of satellite imagery (Conroy et al., 2008; Chang et al., 2009; Kilibarda and Bajat, 2012). Gibin et al. (2008) explain this trend by noting that the API is straightforward to implement, free (with limitations), and, above all, it is a global dataset that is easily accessible by anyone who has access to a computer with an internet connection. Furthermore, the Google interface is limited to basic operations, which makes it more user-friendly than most sophisticated GIS software packages.

### 3.2.3 Vantage Point, Perspective & Alignment

The vantage point determines what is seen in a geospatial image and from which perspective. Three different types of vantage points can be identified: aerial vertical, aerial oblique and ground horizontal (see figure 3.11).

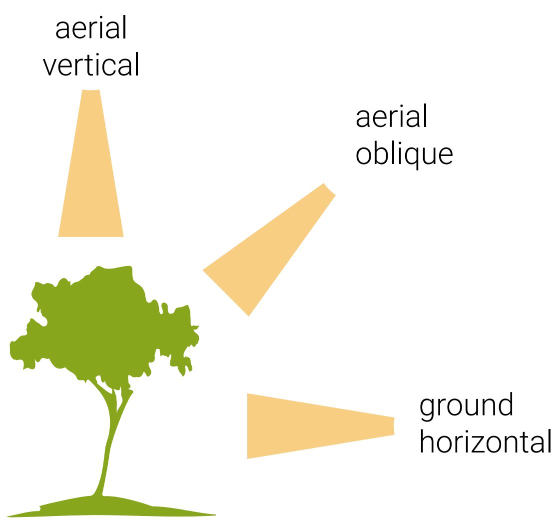



***Figure 3.11*** *Vantage points in geospatial images (Kettunen et al., 2014)*

An aerial vertical vantage point, characteristic for orthophotos, resembles a viewing angle which is orthogonal to the ground. Vertical features, such as building walls or cliffs, are hardly visible from this perspective. Comparisons of efficiency between an aerial vertical and a ground horizontal vantage point have primarily been carried out in urban wayfinding settings. Oulasvirta et al. (2009) and Hile et al. (2008) both conclude that aerial vertical 2D views are better suited for pedestrian navigation than 3D views. According to Oulasvirta et al. (2009), self-location is more efficient when using 2D maps as they provide a bigger picture, which helps users orient themselves in the environment. Usability problems occur when using 3D maps, because they require a lot of interaction to browse the environment.

An aerial oblique vantage point, often called bird's-eye view, resembles a vertical viewing angle which lies between the horizontal and vertical planes. This angle is typically close to 45 degrees, which allows for equal visibility of horizontal and vertical features. Fontaine (2001) promotes the use of an aerial oblique vantage point for the acquisition of spatial knowledge due both to the visibility of landmarks and the configuration of the environment. Distances, however, may be more accurately interpreted when using an aerial vertical vantage point.

A ground horizontal vantage point replicates the view in which humans typically see their environment. The line of sight is a few metres above ground, with a horizontal viewing angle. Most dominant in this view are vertical features, such as building walls. Many experiments have been conducted where traditional 2D spatial representations were compared to virtual 3D environments, which typically try to clone the real-world visual experience (Sjölinder et al., 2005; Waller et al., 1998). Dalgarno and Lee (2010) argue that well-designed 3D virtual environments have the potential to enable learning tasks which are not possible or are less effective in 2D environments. A direct comparison of learning effects between 2D and 3D would reveal that there are minimal benefits if the unique affordances of 3D virtual environments are not harnessed.

Kettunen et al. (2014) reviewed seven frequently used types of geospatial images and evaluated them with regard to different types of knowledge acquisition: landmark knowledge, route knowledge and configuration knowledge. The sizes of the triangles in figure 3.12 illustrate the support of the respective knowledge acquisition. Landmark knowledge, which is based on visual recognition memory, helps with the identification of known places. It is the first kind of spatial knowledge that a child acquires, as well as the first kind of knowledge that adults acquire in unknown environments (Herman and Siegel, 1977). Route knowledge is based on landmark knowledge and reflects the ability to sequentially connect landmarks and paths. Configuration knowledge is based on the understanding of spatial patterns and the organisation of features in relation to each other (Kettunen et al., 2014).

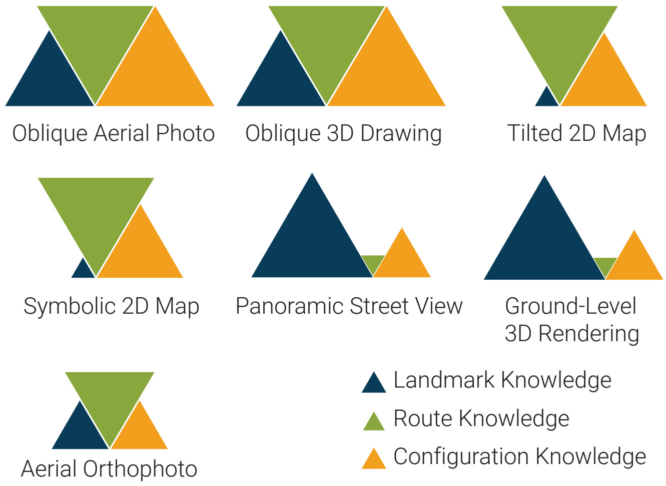



***Figure 3.12*** *Spatial knowledge acquisition (Kettunen et al., 2014)*

According to the 'alignment effect' (Levine, 1982; Roskos-Ewoldsen et al., 1998) shown in several studies on spatial memory, when the 'up' direction on a map corresponds to the 'forward' direction in the participant's surroundings, their accuracy and speed of direction judging is likely to increase. This, however, did not occur for a subgroup of participants studied by Rossano et al. (1995). Nori et al. (2006) found that the alignment effect depends on type of spatial knowledge (e.g. landmark, route or configuration) and whether the spatial information was learned through primary or secondary sources. Landmark participants showed the alignment effect after both primary and secondary learning, route participants only after secondary learning and configuration participants did not show the alignment effect at all.

## 3.3 Interacting with Digital Maps

The *Digital Revolution*, understood as the rapid advance of computing technologies in the late twentieth century and the consequential impact of personal computing on society, together with the *Information Age*, which utilises these digital technologies to produce high volumes of data, has caused numerous innovative changes to the ways in which maps are produced and consumed (Roth, 2014). Digital cartographic interaction, defined as the computer-mediated dialogue between a human and a map, allows for highly responsive systems. Examples are the representation of temporal change through cartographic animation (Lobben, 2003; Harrower and Fabrikant, 2008), data-driven map updates (Boulos and Burden, 2007), and cartographic representations and interfaces that are customized according to use and user context (Reichenbacher, 2001; Friedmannová et al., 2006), and map scale (Brewer and Buttenfield, 2007).

### 3.3.1 Cartographic Scale & Resolution

For a long time the paper map has been the most common way of communicating geographic information. In order to visualise a part of the world on a paper, it needs to be scaled (Longley et al., 2010). A map scale represents the relationship between the distance on the map and the distance on the Earth's surface, which is commonly depicted as a ratio known as the representative fraction (Goodchild, 2008). A small scale map (e.g. 1:1,000,000) represents a large area with few spatial details, while a large scale map (e.g. 1:1,000) covers a smaller area in more spatial detail (Lam and Quattrochi, 1992). In general usage, the term scale is often used to describe the spatial extent of a region and is therefore interpreted to mean the inverse of the cartographic definition. In such usages, large scale refers to large regions (e.g. continental, global scale), and small scale refers to small regions (e.g. individual houses) (Foody et al., 1994). In cartography, a scale of 1:100,000 implies that everything shown on the map is one-100,000th of its actual size, which is not exactly true. Since the surface of the earth is curved, it is impossible to maintain a constant scale throughout the map (Longley et al., 2010). Many authors have described the science of projecting the Earth's surface onto a flat surface using projection methods (Snyder, 1987; Iliffe and Lott, 2008).

Due to the success of paper maps, many principles have been directly adapted to the digital world. Unlike paper, it is not possible to measure distance in a computer. A representative fraction of 1:100 on a digital map implies that 1 pixel represents 100 pixels in the real world, which does not make sense (Jones, 2010). When scale is used in GIS it usually refers to the source scale, which is the scale of the source from which data has been digitised (Longley et al., 2010). A common misconception is that zooming in on a digital map always increases the level of accuracy. Instead, the level of accuracy is determined by its resolution, defined as the smallest recording unit (Laurini and Thompson, 1992). For raster images, this translates to the individual cell size (Heywood et al., 1998).

For vector-based maps, it is advisable to generalise the symbology when zoomed to smaller map scales in order to avoid visual clutter and improve legibility. It is necessary to compromise on how data are displayed, even if this means that some objects or features will be removed or the distortion of features will be unavoidable (Jones, 2010). McMaster and Shea (1992) provide an overview of the most common generalisation methods, which can be subdivided into graphic and conceptual generalisation. When viewing satellite imagery through web-based mapping tools, such as Google Maps or Bing Maps, resolution is typically controlled by tiled mapping clients, triggered through the zoom function. As stated above, the wide success of Google Maps was due to the usability and quick responsiveness of the system. Earlier web-based mapping applications, such as MapQuest and Yahoo! Maps, used clients that requested a new image from the server and re-rendered it every time the map view was moved, even if only a small part of the image was new. Modern applications have been made more responsive through the introduction of tile mapping, which uses background maps that are broken into small tiled images, pre-rendered and stored on a central server. Lower resolution tiles are created by applying a scaling algorithm (e.g. bilinear or bicubic interpolation) to the respective four higher resolution tiles. This process is illustrated in figure 3.13. When the user zooms in or out, the system returns different resolutions of the base image (Sample and Ioup, 2010).

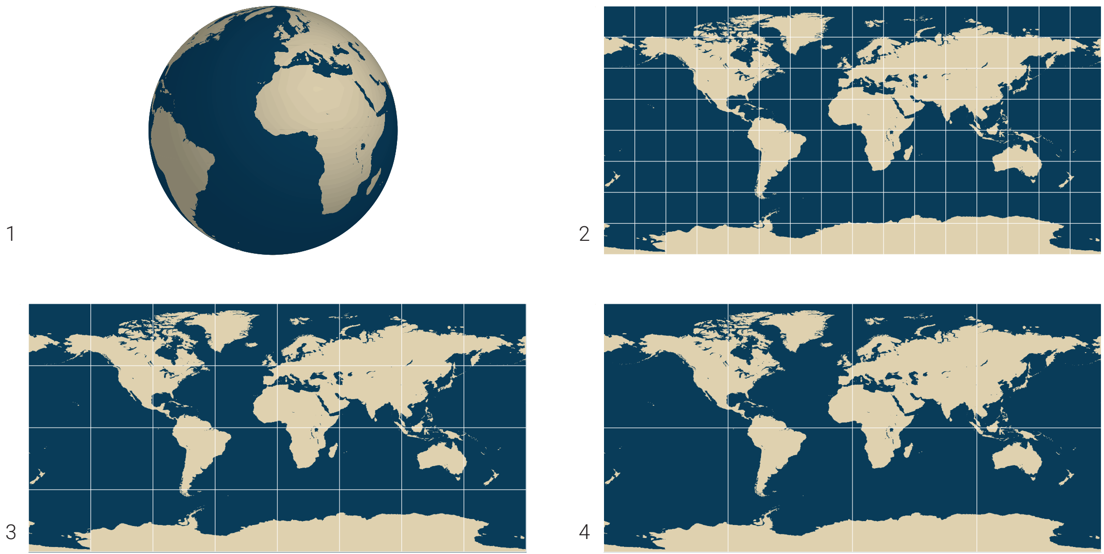



***Figure 3.13*** *Tile creation process, image source: (MacDaddy, 2008)*

### 3.3.2 GIS Interaction & Usability

A current trend in GIS technologies is to provide numerous options for the production, manipulation and representation of large volumes of georeferenced data. The increasing complexity of interactive UIs contributes to user difficulties in operating these systems (Slocum et al., 2001; Gahegan, 2005; Fuhrmann and Pike, 2005; Andrienko and Andrienko, 2006; Wardlaw, 2010). Persson et al. (2006) differentiate between three types of interactivity: interaction with the primary model (e.g. database), interaction with the algorithms for creating a representation, and interaction with the representation model. The latter, which is the subject of this research, includes manipulation of the visual variables such as colour, shape, size and brightness as well as the integration of additional information and zooming and panning interactions. Nyerges et al. (1995) were amongst the first to identify interface design as an important research area for GIS. Andrienko et al. (2002) argue that users must be able to understand and utilise interactive techniques and tools properly in order to extract information and construct knowledge. Harrower and Sheesley (2005) point out three important considerations to make before designing a map interface: kind of control (what type of interactivity is required), degree of control (how much interactivity is required), and the method of control (how system interactivity should be implemented).

As stated in HCI literature, interactive systems require immediate responsiveness. According to Nielsen (1993), a time interval of 0.1 seconds between actions and their completion gives the user the feeling that the system is responding instantaneously. It takes approximately 1.0 seconds before the user's thinking process gets interrupted. After 10 seconds the user loses focus and wants to perform other tasks. In this case feedback should be given about the expected time the system requires to finish the task. According to the Keystroke-Level Model (discussed in section 4.1.1), response times should be 0.40 seconds for a keyboard press, 1.16 seconds for a coarse mouse movement, and 0.38 seconds for a fine, honing mouse movement (Card et al., 1980). In the context of geographic datasets, which typically have high data volumes and expensive calculations, the time limits outlined are rarely achieved (Haklay and Li, 2010).

Harrower and Sheesley (2005) examined nine common methods for panning and zooming in order to identify the best implementation for improving users' productivity, comfort and efficiency when interacting with digital maps. Previous studies that investigated scrolling efficiency concluded that it is highly dependant on the specific tasks that users are trying to accomplish (Hinckley et al., 2002; Cockburn and Savage, 2004), as well as user characteristics and prior experience. Research has shown that people acquire interface skills largely through exposure and repetition. Harrower and Sheesley (2005) conclude that there is no one-size-fits-all solution, and that good mapping systems should incorporate multiple methods for panning and zooming.

The collection *Exploring Geovisualization* (Dykes et al., 2005) provides an overview of interactive GVis technologies by emphasizing the importance of human factors. Slocum et al. (2001) describe a six-stage design process for the creation of a user-centred GIS tool to visualise issues related to water balance. Haklay and Zafiri (2008) evaluated the usability of interactive GIS applications by analysing screenshots users took during their working day. Davies (1998) conducted a participant observation experiment in which GIS analysts were video-taped while engaging in their daily work. A coding scheme following Whitefield et al. (1993), was developed that distinguishes between work actions, which accomplish the desired goal, and enabling actions, which prepare for or clean up from work actions. To achieve efficiency, enabling actions should be limited to a minimum. The experiment revealed that most participants spent about 10-20% of their time performing GIS work actions with no participant spending more that 30% of their time on actual work action. Roth (2014) states that highly interactive GIS do not necessarily add value to cartographic representation. This idea is further promoted by Jones et al. (2009), who conducted a user experiment evaluating a minimalistic design approach to GVis according to the usability measures efficiency, effectiveness and learnability. The system UI was informed by Buxton's (2001) "less-is-more" approach. Roth (2014) argues that there are situations within GVis when the provision of interaction is justified. For instance, cartographic interaction can allow the user to customise the communicated message to his or her particular context and interests. Furthermore, cartographic interaction may allow the user to communicate additional details once the overview has been understood. Finally, digital cartographic interaction gives the user a sense of control over the experience and thus increases his or her motivation to study the map.

This section provided an overview of usability studies regarding GIS and digital map interaction. The mentioned studies were carried out in regions where maps and geographic data exist in abundance and typically easy to access. Experiments conducted for this research are located in areas where detailed, high-resolution cartographic visualisations are sparse or not existing. Thus, the creation of maps as a required first step to studying map understanding is addressed in the next section.

## 3.4 Summary

This chapter presented an overview of map creation methods to support participatory mapping activities and studies in regions that are lacking detailed cartographic visualisations. In the field of Remote Sensing, data to generate orthophoto maps have traditionally been acquired through sensors mounted on a satellite platform or manned aircraft. The 'drone revolution' along with advancement in the field of Computer Vision have put powerful mapping tools in the hands of non-specialists, enabling the study of appropriate processes to generate suitable maps for this research.

Finally, existing literature on the understanding and use of interactive mapping environments as well as the creation of orthophoto maps were reviewed. Generally, reading a map requires the reader to understand the correspondences between the map and the space that it describes. High visual realism in geospatial images has an effect on the cognitive processing of the viewer as it facilitates interpretation but requires extraction of the relevant features. The advent of computer-based visualisation of geospatial data has stretched traditional cartographic domains of visual communication allowing for multiple layering as well as interactive zoom level adjustments. The increasing complexity of interactive GIS

UIs contributes to user difficulties in operating these systems but at the same time has the potential to give the user a sense of control over the experience and thus increases his motivation to study the map.

# 4 Related Work in Human-Computer Interaction and Action Research

This chapter reviews the principles and methods used in the field of Human-Computer Interaction (HCI) and Action Research (AR), which underpin the work on the research of evaluating the suitability of digital mapping tools for non-literate users. The design of UIs for users who are new to digital technologies and conventions presents a particular challenge to software design. In this research, HCI methods are adapted to evaluate the usefulness and usability of a system. HCI is a multidisciplinary subject that is primarily concerned with the design, implementation and evaluation of interactive systems by trying to understand how people interact with them in order to accomplish tasks. HCI's rigorous focus on specific scientific processes and goals does not always adapt well to research that intends to solve problems by directly working together with the people affected by them (Hayes, 2011). The field of Action Research may supplement HCI's methodologies to better enact social change.

The first section introduces the field on HCI with User-Centred Design (UCD) and usability as its core principles. The concepts of inclusive design and universal usability are then introduced given the social context in which digital technology is applied in this research. As Intelligent Maps (see section 2.4) foresees the use of portable technology, the challenges that need to be addressed when designing for mobile devices are outlined before introducing the progress in the field of Human-Computer Interaction for Development (HCI4D). Finally, an overview of the history, concepts and deployment of Action Research is presented.

## 4.1 Human-Computer Interaction and Interaction Design

HCI builds on a wide range of disciplines, including cognitive science, psychology, ergonomics, computer science, engineering, and graphic and industrial design. HCI emerged during the 1970s, originating from the fields of ergonomics and 'Man Machine Interaction' (Haklay and Skarlatidou, 2010). Since then, the field of HCI has expanded rapidly and attracted professionals, who incorporate diverse concepts and approaches. Generally, it can be said that *Human* stands for the user or group of users that is trying to achieve something with the help of technology. *Computer* implies any technology, ranging from large-scale distributed systems to mobile devices. It can also refer to non-technical parts. *Interaction* means the communication between the user and the system, which can either be direct or indirect (e.g. through sensors).

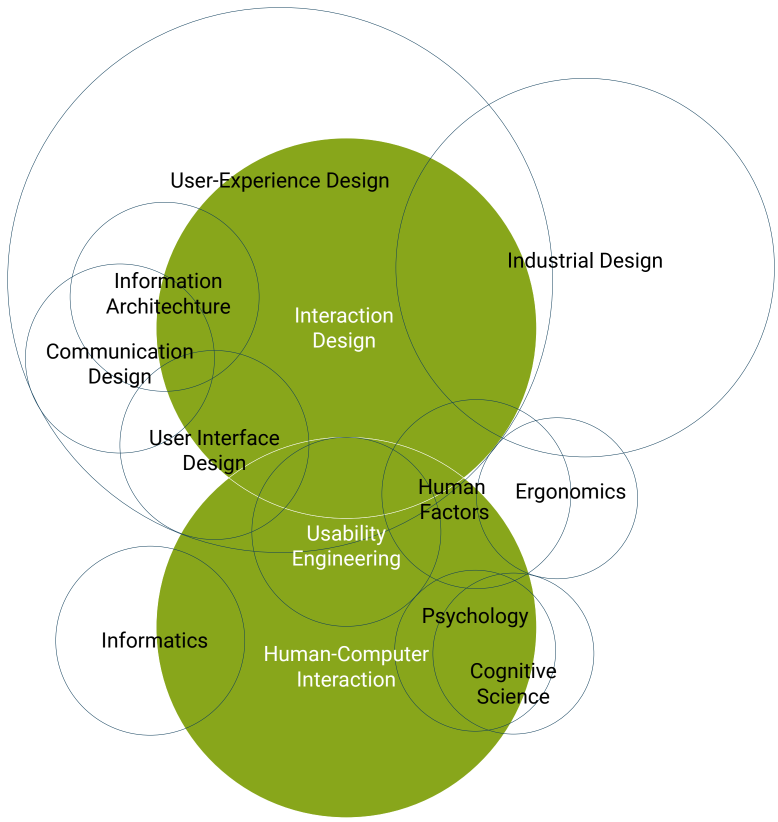



***Figure 4.1*** *Overlapping disciplines in HCI (adapted from Saffer, 2010)*

HCI is closely related to the field of Interaction Design (IxD). Cooper et al. (2012: p.xix-xx) describe IxD as "the practice of designing interactive digital products, environments, systems, and services. [...] It is concerned most significantly with satisfying the needs and desires of the people who will interact with a product or service". Similar definitions have been given by Saffer (2010), Garrett (2010) and Rogers (2011). The boundaries between disciplines, related to HCI and IxD are fuzzy and not clearly defined. Figure 4.1, based on Saffer (2010), illustrates their position within the wider field. It is often claimed that IxD draws its traditions and methods from the practice of design while HCI has a strong background in computer science and is mainly research focused (Norman, 2013). Dix (2004: p.192) introduces his chapter about IxD as follows: "Some of HCI is focussed on understanding: the academic study of the way people interact with technology. However, a large part of HCI is about doing things and making things – design."

A number of generic IxD principles have been provided by Norman (1999) and Rogers (2011) to serve as best practices for good design. The most common ones are visibility, feedback, constraints, consistency and affordance. The principle of *visibility* states that all essential functions should be clearly visible and obvious to the user. Problems occur when clues are either lacking or when they exist in excess. The concept of *feedback* describes the necessity of communicating the results of an action. Feedback must be immediate, informative and appropriate. *Constraints* limit the user to the options that are appropriate at a certain time. A common practice in UI design is to disable options by shading them grey and thereby prevent the user from selecting incorrect options, but indicate their potential availability. It is important to have *consistent* concepts for the same actions, which allow the user to learn how to use the system. Inconsistent UIs lead to confusion and provoke errors. *Affordance* refers to the ability to instinctively understand a design without the need of further explanation. A door handle, for instance, affords pulling. Screen-based UIs do not have real affordances, but perceived affordances, which essentially are learned conventions.

The underlying aim of HCI is to make interactive systems more usable. Usability is a quality that only becomes an issue when it is missing. Typically, it is the absence of frustration that characterises usability. If the user is forced by the system to adapt to an unacceptable mode of work, it is unusable. There is no general agreement on how to ensure usability but several authors have proposed measures of usability (Nielsen, 1993; ISO 9241-11, 1998; Shneiderman and Plaisant, 2004; Dix, 2004). These measures are further described in appendix A.1.

In order to create usable systems, the User-Centred Design (UCD) approach is nowadays widely recognised (Abras et al., 2004; Norman, 2005). ISO 9241-210 (2010) defines UCD as: "An approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques". The core method of UCD is the iterative design cycle with four activities, which are repeated with each iteration showing improvements towards the desired solution. The individual steps are: observation, idea generation, prototyping and testing. See appendix A.2 for more detail on UCD.

### 4.1.1 Usability Engineering

The field of Usability Engineering (UE) is the process of applying measures against which the product can be judged to ensure usability. Ideally, the evaluation should be part of the iterative design process in order to ensure that the results feed back into modifications to the design (Dix, 2004; Haklay et al., 2010). UE has three main goals: the assessment of the extent and accessibility of functionality, the assessment of users’ experience of the interaction, and the identification of problems with the system (Nielsen and Molich, 1990). Usability evaluation methods can be divided into two main groups: *analytical methods*, carried out by experts using specific guidelines, and *empirical methods*, interviews with and observations of actual users. Table 4.1 provides an overview of popular UE methods, which are further discussed in the remainder of this section.

***Table 4.1*** *Comparison of usability evaluation techniques (Holzinger, 2005)*

| | Analytical Methods | | | Empirical Methods | | |
|---|---|---|---|---|---|---|
| | **Cognitive Walktrough** | **Heuristic Evaluation** | **Keystroke-Level Model** | **Thinking Aloud** | **Field Observation** | **Questionnaires** |
| **Applicably in Phase** | all | all | design | design | final testing | all |
| **Required Time** | medium | low | high | high | medium | low |
| **Needed Users** | none | none | none | 3+ | 20+ | 30+ |
| **Required Evaluators** | 3+ | 3+ | 1-2 | 1 | 1+ | 1 |
| **Required Equipment** | low | low | low | high | medium | low |
| **Required Expertise** | high | medium | high | medium | high | low |
| **Intrusive** | no | no | no | yes | yes | no |

### Analytical Methods

Due to budget and time restrictions, it is rarely possible to carry out extensive and repeated user testing throughout the design process. In this case, analytical methods, such as Cognitive Walkthrough (CW), Heuristic Evaluation (HE) or Keystroke-Level Model, should be used to eliminate problems before considerable effort and resources are spent on the implementation process (Dix, 2004).

Cognitive Walkthrough (CW), originally proposed by Polson et al. (1992), is a task-oriented method in which peers assess the usability of a system early in the design process and identify causes of usability problems. The evaluators put themselves in the position of potential users and try to uncover discrepancies between the assumptions made by the systems designers and the knowledge and behaviour of future users. The idea is to re-enact the mental processes of users while operating the system. Experience shows that users prefer to learn new systems in an exploratory way rather than reading manuals and documentations (Blackmon, 2004; Imai et al., 2010), which is taken into consideration during a CW session. The required inputs are an interface's detailed design specification, a prototype or a working system, a task description including all the actions needed to successfully perform the task, and explicit assumptions about the users, their experience and knowledge. During the process the peers consider the users' actions required to perform the task. For each step, the analyst reflects on what the user would do at that point in order to achieve the specified goal. If the IxD principles have been implemented correctly, the available options in combination with appropriate UI design, should cause the fictive user to select the right action. Subsequently, the user should be presented with clear feedback indicating his or her progress towards task completion (Wharton et al., 1994; Nielsen, 1994; Rieman et al., 1995; Dix, 2004). A common risk when applying expert evaluation is the potential discrepancy between the future users' and the evaluators' actions. Furthermore, the CW's only focus is ease of learning. Wharton et al. (1994) argue that other usability measures, such as ease of use and functionality, are correlated with ease of learning. Hence, if the system's functionality does not match the user's needs and forces them to perform multiple actions in order to accomplish a single task, the application will be difficult to learn. However, if the CW is used as the only evaluation method it might introduce a bias towards ease of learning at the expense of other features.

In Heuristic Evaluation (HE), developed by Nielsen and Molich (1990), a group of HCI experts analyse the usability of a system with the help of certain guidelines and principles, called heuristics. HE can be applied to design specifications, prototypes or fully functioning systems. Similar to the CW, it is a relatively cheap approach and it is useful for evaluating the system early in the design process. It is important for the evaluation to be carried out multiple times independently by different evaluators. Nielsen found that three to five evaluators find 40-60% of known issues through heuristic evaluation (Nielsen and Molich, 1990). In order to facilitate and structure the evaluation process, a set of ten heuristics, developed by Nielsen (2005), are provided. If necessary, these can be modified or extended according to the system to be evaluated. In the assessment process, the evaluators make notes about violations of the heuristics including the severity of each problem. Once the evaluators have finished their assessments, the mean severity ratings are calculated and presented to the design team (Dix, 2004). The advantage of this method is that it is simple, quick and inexpensive. The procedure is very easy to learn and can be performed without additional equipment. However, the method often reveals problems without giving indications on how to solve them. Another issue is that, despite the formal nature of the heuristics, the results often reflect the evaluators' current mindsets and subjective opinions (Nielsen and Molich, 1990).

One of the earliest methods used in UE was the Keystroke-Level Model, developed by Card et al. (1980). It breaks a task down into low-level operations, such as keystrokes, and assigns a predicted time to each of them. The analysis process includes counting each keystroke and mouse movement, the required time to switch between keyboard and mouse, mental preparation and system response time. In Card et al. (1980), the authors empirically validated their proposed times against ten different systems and obtained an average prediction error of 21% for individual tasks. The Keystroke-Level Model is easy to implement and does not require any real users. However, it is limited to the evaluation of efficiency and disregards other measures of usability.

**Empirical Methods**

Despite the advantages provided by analytical evaluation methods, it is indispensable to carry out real user testing as part of the design process. This provides first-hand information about the way people use a system and what exact problems occur while doing so. Various ways of conducting empirical usability tests exist. Some of the most common ones are 'Thinking Aloud', field observation and questionnaires (Holzinger, 2005).

The Thinking Aloud technique is a form of observation, where the user is asked to continuously provide commentary while using the system. By verbalising their confusion, frustration or enjoyment, the user reveals their view of the computer system as well as potential misconceptions. Having users interpret individual interface items can provide useful insight into problems and helps in identifying their source. The great advantage of the Thinking Aloud method is its simplicity in capturing information on preference and performance simultaneously. However, the main risk is that the participants may feel self-conscious which may alter their behaviour. Often, this mindfulness prevents the user from making errors that might have occurred in a real situation (Nielsen, 1992; Dix, 2004). A variant of this method, called Cooperative Evaluation, involves two participants who use the system together while communicating with each other. It is believed that this situation appears more natural to the participants and often leads to more comments through constructive interaction (Holzinger, 2005; Rubin and Chisnell, 2008).

The Field Observation method requires the evaluator to observe the participants in their workspace while either performing a given task or going about their normal duties. Ideally, the observer does not attract attention. To guarantee authentic conditions, they should be virtually invisible (Holzinger, 2005). Several methods are commonly used in order to record user actions: paper and pencil, audio recording, video recording, computer logging or user notebooks. Although video recording is usually less obtrusive, the time required to analyse the material requires approximately ten times that of the test (Dix, 2004). If not using the Thinking Aloud method, it is rarely possible to extract useful information from audio recordings and it is difficult to match it up with with other protocols, such as handwritten notes. Computer logging is relatively easy to implement and unobtrusive. However it only gives information on what the user's actions were and reveals nothing about why and how they were performed. Just like video or audio tapes, automatic logging can result in vast amounts of data, which might be difficult to manage if the analysis is not automated. In practice it often makes sense to use a time-synchronised combination of these techniques.

Issues about subjective (dis)satisfaction when using a system, as well as users' frustrations or delight, can be studied by questioning the users. This method does not directly evaluate the user interface, but people's opinions. People's statements about what they do often do not reflect their real behaviour and therefore results may have low validity. In order to be able to compile significant results, a high number of participants is required. Holzinger (2005) believes that the minimum number of participants should be 30. Advantages of this method include the ease with which subjective user preferences can be identified. Furthermore, questionnaires are useful for generating quantitative results and statistics.

In many cases it is useful to apply various complementary evaluation methods. A CW can be supplemented with HE due to its task-independence. Similarly, it makes sense to combine direct methods (e.g. Thinking Aloud) with indirect methods (e.g. Questionnaires). Most important with any kind of testing is to understand the users' task, culture and capabilities (Holzinger, 2005).

### 4.1.2 Inclusive Design & Universal Usability

The need to address various different user capability levels has led to the emergence of Inclusive Design. "Inclusive Design is neither a new genre of design, nor a separate specialism. It is a general approach to designing in which designers ensure that their products and services address the needs of the widest possible audience, irrespective of age or ability." (Design Council, 2008) Essentially, Inclusive Design is the inverse approach to earlier practices, which aimed to specifically design for disabled and elderly populations. Inclusive Design breaks with this traditional pigeonholing and seeks to integrate older and disabled people into mainstream society. Human interactions increasingly rely on devices, which can be either enabling or disabling. It should be taken for granted to design a world that matches human diversity by addressing the challenge of designing enabling devices for the whole population (Clarkson and Coleman, 2013).

History has shown that considering people with alternate needs in the design process has often led to more usable products for everyone. One example, described by Norman (2013), is Sam Farber's plan in the late 1980s to develop household tools that were usable by his arthritic wife. The commonly used vegetable peelers at that time were simple metal tools that were awkward and painful to use, and not very effective, but it was assumed that this was how they had to be. Farber did extensive research and eventually selected a design with fat black handles of soft plastic, shaped and angled to be comfortable in the hand. Farber founded the company OXO, promoted his products as being better for everyone, and set a new standard for vegetable peelers which is still widely used today. Similarly, Maria Benktzon and Sven-Eric Juhlins of Ergonomidesign, focused on the idea of "design for a broader average" (Clarkson, 2003: p.15), which led to an extensive rethinking of commonly used products. The design processes for eating implements, walking sticks and coffee pots are outlined in Benktzon (1993). Their key strategy was to target design at the broad public in terms of cost and appearance, while accommodating those with restricted capabilities in terms of performance and functionality. Benktzon (1993) identified that the key problem for people with arthritis using a conventional walking stick was poor contact between the palm and the supporting areas of the handle. In the new design, the contact area was increased considerably by an anatomical handle which provided better support. This new design turned out to be less painful and more enjoyable for a wide range of people.

Ben Shneiderman was among the first to promote the idea of *Universal Usability* within the field of HCI. In 1997 he wrote an essay, titled *Between Hope and Fear* (Shneiderman, 1997), in which he expressed three wishes, one of them being "Universal Access to Computing Technology". In this he states that: "Applications and services will have to be re-engineered to meet the differing needs of the many still forgotten users" (Shneiderman, 1997: p.60). Habitual exclusion of specific user groups from access to information and participation is contradictory to the notion of a fair society, and therefore it is an indispensable goal to design systems that are accessible and usable by everyone. Although major advances have been made in the field of HCI over the past two decades, and despite many efforts in inclusive interface design, Universal Usability remains a major challenge.

A successful example of Inclusive Design for technology is the predictive text system T9. Before the breakthrough of smart devices using QWERTY keyboards, T9 had been prevailingly used for text messaging on mobile phones (Jones and Marsden, 2006). The original goal was to develop a system that enables impaired users, who can only control their eye movements, to enter text on a computer. Since the human eye can only focus accurately on eight different regions, the idea was to group letters together in eight clusters and develop special glasses that identify people's focus. While moving the eyes from one cluster to another, a dictionary function is used to suggest potential word matches. Similarly to the users who are restricted to the eight regions of eye-movements, a mobile phone user is restricted by the small size of the device and the limited number of buttons on the device's keyboard. The company Tegic saw the potential in adapting this predictive system in order to simplify text-entry and integrated it in mobile devices.

Despite the existence of design which successfully incorporates solutions for people with special requirements, it is fair to say that systems like T9 are not universally applicable. It still excludes a vast number of people, such as non-literate user groups. Shneiderman (2000) suggests defining Universal Usability as "having more than 90% of all households as successful users of information and communication services at least once a week." This implies that, in addition to universal access, successful use is a central requirement. He points out three core challenges for Universal Usability:

- Technology variety: Supporting a broad range of hardware, software, and network access;
- User diversity: Accommodating users with different skills, knowledge, age, gender, abilities, literacy, culture, income, etc.;
- Gaps in user knowledge: Bridging the gap between what users know and what they need to know to use new tools successfully.

Hertzum (2010) argues that most people – including designers – have the tendency to believe that other people are quite similar to themselves and therefore consistently underestimate the challenges of Universal Usability caused by the great variety in human abilities, backgrounds, personalities, values and access to information. This variety makes it unlikely that a single product can be accessible to everyone. Based on the User Pyramid concept, following Benktzon (1993), where different bands indicate the user's impairment level, Keates et al. (2002) developed the model of the Inclusive Design Cube in order to communicate the needs of diverse users while emphasising the varied capability levels of the users and the need for modular and customisable designs. The axes of the cube represent different user capabilities and the enclosed volume indicates the system coverage of the user population. Hertzum (2010) seized on Shneiderman's three challenges and mapped them onto a similar Inclusive Design Cube in order to illustrate the population coverage of a system. The example in Figure 4.2 shows the cumulative effect of a design that covers 80% of user diversity, 80% of knowledge gaps and 80% of technology variety, which results in a system coverage of only 51% (assuming that the dimensions are independent).

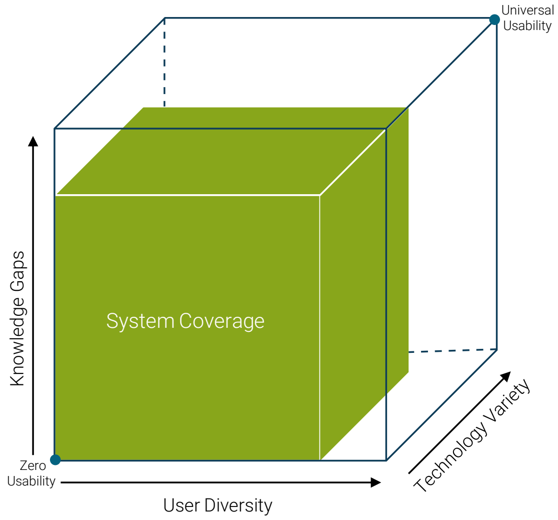



***Figure 4.2*** *Inclusive design cube (Hertzum, 2010)*

In their research, Keates et al. (2002) and Hertzum (2010) raise the necessity of modular and customisable products for different levels of impairment and capabilities. Similarly Stephanidis (2001) claims that 'User Interfaces for All' should not be understood as the attempt to produce a single solution which fits all needs, but rather as a new way of thinking that paves the way for universal access.

### 4.1.3 Design for Mobile Devices

The rise of smart mobile devices, which are approaching desktop computers in technical sophistication, radically changed the world of computing by introducing new features and concepts such as multi-touch interfaces, integrated sensors and mobile internet connectivity. Increasing capabilities and value-added features typically induce complex UI designs. Furthermore, designers for mobile environments need to consider limited screen size and resolution, limited processing power, limited battery life and divergent mobile platforms. Traditional approaches in software and usability engineering are not sufficient and new challenges need to be addressed. Dehlinger and Dixon (2011) identify the main challenges as being the creation of user interfaces accessible to users with different abilities, design for multiple platforms, and the design of context-aware applications.

Oehl et al. (2007) argue that UI items on mobile screens should be large enough to be tapped successfully but small enough to be able to display all the necessary information and navigation components on one screen. In their research, they look into the correlation between screen size and pointing performance using a stylus pen. They conclude that display size and task difficulty affect movement time and errors. Overall, performance increased with increasing display size and with decreasing task difficulty. Balagtas-Fernandez et al. (2009) conducted a user study and evaluated the usability of different UI designs and input methods for smartphones. Hoggan et al. (2008) suggest using tactile feedback in touch screen devices to imitate some of the lost feeling of operating a physical keyboard. In their experiment, tactile feedback significantly improved the users' text entry performance. Norman and Nielsen (2010) criticise gestural interfaces, claiming that so-called 'natural interfaces' are not natural at all and violate fundamental principles of interaction design. Mauney et al. (2010) analysed user-defined gestures for commonly used actions, such as scroll, rotate and zoom, and tested them for similarities across nine countries. Generally, they found a high level of agreement across cultures, especially on direct manipulation gestures (e.g. move, rotate). The agreement on symbolic actions (e.g. accept, delete) was slightly lower.

An exhaustive guide for best practices in mobile map communication based on spatial data visualisation and graphic design theory is provided by Muehlenhaus (2013). He points out the three factors affecting a digital map layout are screen size, resolution and density. Clark (2010), additionally, stresses the point of ergonomics when designing for handheld devices. For instance, he advises putting primary controls in the thumb's 'hot zone' at the bottom of the screen and placing edit buttons at the top where they are unlikely to make accidental changes. These principles change with screen size. When using a tablet, the primary thumb zones are the top corners.

Today's smart mobile devices are available with a range of different operating systems (e.g. Android, iOS, Windows 7), running on different computing platforms (e.g. smartphone, tablet) built by various manufacturers (e.g. Apple, HTC, Samsung, LG), and suitable for different delivery methods (e.g. native applications, web applications) (Dehlinger and Dixon, 2011). In addition, each device typically receives several software updates over its lifetime (Cha and Yun, 2013). When aiming at a broad user range, or Universal Usability, all of these options must be taken into account, resulting in a major design and programming effort. In recent years, a number of cross-platform frameworks have emerged, which can be divided into two categories: cross-compilation techniques that transform platform-independent code into platform-specific native apps, and HTML5/CSS3 frameworks, that allow for cross-platform interfaces to run in web browsers. Popular cross platform frameworks, such as PhoneGap, Rhodes or Titanium, typically combine both methods (Allen et al., 2010; Hartmann et al., 2011). Despite the technical possibility of creating web apps that run on various platforms, Rauch (2011) points out the fact that different platforms require different design.

Context awareness has existed in the field of computer science since the early 1990s. Abowd et al. (1999) suggested definitions for the terms 'context' and 'context-awareness' that have since become widely accepted (Perera et al., 2014). Modern mobile phones commonly include a large number of sensors (e.g. accelerometer, GPS receiver and gyroscope) and it is predicted that this number will grow substantially within the coming years, generating Big Data (Sundmaeker et al., 2010; Zaslavsky et al., 2012). It is often argued that data only becomes valuable once it has been processed and turned into information, also defined as "data in context" (McNab and Ladd, 2014). Part of this information is the communication of measurement uncertainty. Although many technical frameworks have been suggested in order to integrate context-awareness (Ramparany et al., 2007; Bernardos et al., 2008; Martin et al., 2010), Häkkilä and Mäntyjärvi (2006) point out the need for UI design guidelines for context-aware mobile applications.

### 4.1.4 HCI4D

Mobile technology is on the rise in developing countries, not least due to technological leapfrogging (Mansell, 2001). The number of mobile subscriptions worldwide has increased from less than 1 billion in 2000 to more than 6 billion in 2012, with nearly 5 billion in developing countries (World Bank Group, 2012). Despite that upsurge, the hoped-for success in bridging the 'digital divide' has not materialised to date. Many attempts failed due to so-called 'technological imperialism', where solutions from the developed world are applied in developing countries without the necessary adaptations to local context. Jones and Marsden (2006) claim that it is not enough to just internationalise UIs by changing the language or replacing text with icons, but it is fundamental to understand the target users' visual literacy and their ability to interpret signs and diagrammatic conventions. To date, most of the research into cultural interpretation of visual interfaces is conducted in the form of a controlled lab experiment, limited to guidelines on appropriate use of colours and icons (Shen et al., 2006; Slay and Dalvit, 2008).

By now, the relevance of using local languages and dialect is widely accepted amongst the HCI4D community when new products or designs are tested (Ho et al., 2009). Images are used as a replacement for text and UIs are designed in minimalistic and simplistic ways. In line with the idea of inclusive design, it is being argued that best practices in low literate interface design could improve usability amongst literate users as well (Kumar et al., 2017). Much influential work on addressing low literacy and UI was carried out by Indrani Medhi Thies (e.g. Medhi et al., 2005; Medhi, 2007; Medhi et al., 2009, 2010; Medhi Thies, 2015).

Multiple researcher have found that hierarchical structures in UI navigation do not well represent oral knowledge communities (Medhi et al., 2013; Winschiers-Theophilus et al., 2010; Vitos et al., 2017). However, research suggests that low-literate mobile phone users often develop coping strategies such as rote memorisation or visual cues (Chipchase, 2006, 2008; Knoche and Huang, 2012). Smyth et al. (2010) show how phone users in India manage to overcome a range of technical and socio-economic obstacles driven by the strong desire to access media sharing services. Apart from UI design recommendations, Medhi's work has shown that there are more obstacles to usability than poor literacy. They include lack of confidence with the technology and inexperience with procedural instructions. These factors play a significant role when it comes to research and experiment design. Yet, research methodologies in the field of HCI4D are still relatively unexplored.

Goncu-Berk (2015) employed a grounded theory methodology to understand the challenges when conducting design research in other cultural contexts. She interviewed twenty designers who have carried out field studies in cultures significantly different than their own and identified main challenges. Building relationships despite the 'otherness factor' was often referenced as a challenge, meaning that western researchers are perceived as wealthier outsiders and power figures that can provide physical or financial solutions immediately. Time constraints and communication barriers were commonly named as reasons for missing out on contextual information.

Medhi (2007) reports about her experience of applying UCD in the development context and emphasises the importance of unlearning certain preconceptions about common theories of HCI. She further describes the value of spending as much time as possible with unfamiliar communities to gain their trust, which is best facilitated by local, trusted intermediaries. Thereby it is important to pay special attention to subtle details in social, religious and cultural affiliations in order to avoid unintended interpretations especially in relation to UIs. The final point she makes is to be flexible with evaluation techniques to ensure mental comfort of the research participants. UCD in the developing world requires innovations in design processes and adaptations to established processes to fit the specific context. In her research, she used methods in which tasks were embedded in dramatised stories, which motivated the participants towards the desired tasks.

In traditional usability research, the user is viewed as an individual interacting with technology on their own. In certain circumstances, however, this concept goes against the main principle of UCD, which is to consider the context in which a technology is used. Kumar et al. (2017) conducted parts of their usability study in groups, which often led to the person quickest to learn teaching the rest. This scenario often reflects reality, in which a relative or friend demonstrates how a technology works. Especially in community focused groups, such as egalitarian societies, the communal way of life should be considered in research design.

Popular research methods in HCI have been developed in western cultures and may not work properly in different cultures. Lee and Lee (2009) conducted comparative experiments interviewing focus groups in the Netherlands and South Korea. The communication styles of the two cultures varied significantly. Dutch participants told narratives followed by discussions amongst themselves. Koreans showed much weaker participation and tended to give only short answers.

Hayes (2011) points out that the application of HCI and UE research methods in a cross cultural and socially relevant context needs to go beyond the purpose of contributing to the academic body of literature, by providing a meaningful contribution to the research participants. She argues that, despite the increased interest in participatory approaches in addressing 'real human problems', some researchers are still concerned about how scientific and systematic these methods are. To address this issue, a combination of HCI and Action Research (AR) has been proposed by researchers including Foth and Axup (2006); Ferrario et al. (2014). The remainder of this chapter discusses the use of AR and its relationship with HCI.

## 4.2 Action Research

Action Research (AR), as defined by Reason and Bradbury (2008) links practice, ideas and research to promote human and environmental development and facilitate positive social change. Rather than a methodology, AR is seen by the two authors as an 'orientation to inquiry' which seeks to resolve issues within a community. AR is highly participatory, bringing together action, reflection theory and practice in the pursuit of practical solutions "to issues of pressing concern to people, and more generally, the flourishing of individual persons and their communities" (Reason and Bradbury, 2008: p. 4).

AR is two-faceted – on the one hand it creates philosophically sound and pragmatic knowledge, and on the other hand it focuses on practical knowledge in order to improve personal and professional life (Reason, 2012). Reason and Bradbury's AR approach is built on the work of the German-born social psychologist Kurt Lewin as well as on studies conducted by researchers at the Tavistock Institute in the 1940s. In a series of socio-technical experiments on the topics of inter-group relations, eating habits and prejudice, Lewin aimed to solve social problems and assist organisational change (Greenwood and Levin, 2006; Stebbins et al., 2009). His approach was also put into practice by the Tavistock Institute to treat psychological disorders on soldiers after the Second World War (Kock, 2011).

When Lewin coined the term in 1948, AR was "a comparative research on the conditions and effects of various forms of social action and research leading to social action". He suggested that the process includes "a spiral of steps, each of which is composed of a circle of planning, action, and fact-finding about the result of the action" (Lewin, 1948: p. 203). Although AR has undergone substantial changes since its beginnings, it still consists of the spiral of steps as per Lewis' definition above. Figure 4.3 presents the four major phases within the spiral, i.e. "planning, acting, observing and reflecting" (Zuber-Skenitt, 1993: p.46). After the completion of the fourth phase of reflection in AR, the researcher repeats the four phases as many times as it takes to resolve the issue and provide a solution (Coughlan and Coghlan, 2002).

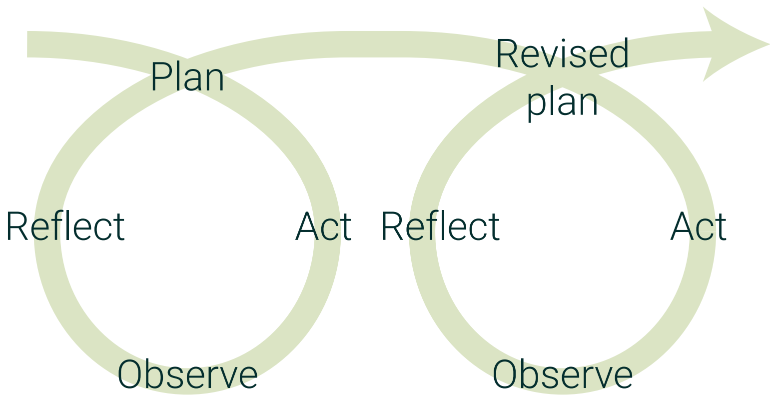



***Figure 4.3*** *Action research spiral after Zuber-Skenitt (1993)*

When AR is implemented with the intention of making changes in a collaborative fashion, the research approach becomes participatory. This branch of AR is known as Participatory Action Research (PAR) and enables community participation and problem reflection (Baum et al., 2006; Reason and Bradbury, 2008). Researchers and participants collaborate to understand a problem by collecting and analysing data. Based on their findings, they attempt to solve the issue, and continue on to reflect on the collected data and action (Baum et al., 2006). PAR also follows AR's spiral of phases as each action is followed by a reflection where the outcomes of the action are evaluated. PAR is driven by willing communities with an aim to collect, produce and use knowledge to change or solve the issue (Pain et al., 2011). The PAR approach requires researchers to be democratically and actively involved with a local community as a result of which they take on a variety of different roles during the approach such as that of a 'facilitator', 'process-planner', 'analyst', 'evaluator', 'co-ordinator' and/or 'change agent' (Rasmussen, 2004).

Since its inception, AR has been embraced as a research approach in, amongst others, education, health and nursing (Easterbrook et al., 2008; Medeiros dos Santos and Travassos, 2009). It is only in the recent years, however, that the field of software engineering has seen an increase in the use of AR (Medeiros dos Santos and Travassos, 2009). Since software engineering aims to provide technological solutions within organisations and communities, AR has become an ideal approach (Medeiros dos Santos and Travassos, 2009). It is, for example, used by Ianzen et al. (2013) in order to increase software quality in a financial institution and to motivate the organisation's technical team, as well as by Iversen et al. (2004) for exploring ways in which software development can be improved in collaboration with four Danish organisations. Similarly, Wastell et al. (2004) are using AR to develop information systems for crime reduction and Read et al. (2013) are exploring the applicability of PAR in the development of a bereavement ICT tool.

These projects illustrate how researchers are embracing AR to tackle existing issues with the active involvement of users. They follow an iterative multi-step approach, adjusting their actions depending on the continuous flow of collected information (Coughlan and Coghlan, 2002). Moreover, most software engineering research projects reported in literature can be seen as using a form of AR since projects are generally developed and evaluated together with users or organisations followed by a reflection on the outcome (Easterbrook et al., 2008).

According to Siew et al. (2013), software development and ICT solutions usually address the needs of users in western urban settings. Hence engineers designing and developing ICT system for rural communities in remote and extreme environments face social, practical and technological challenges (Irani et al., 2010; Vitos et al., 2017). ICT4D professionals must assess how to design solutions in a local context they do not understand (Blake, 2016). In addition, a lack of technical knowledge due to little or no prior exposure to technology in remote and extreme locations limits local interest in ICT-based solutions. Subsequently, as Heeks (2002, 2010) states, half of the projects conducted under such circumstances have been total or partial failures. According to Oyugi et al. (2008), there is also an issue when it comes to western methodologies as they cannot be applied when evaluating ICT systems in different contexts. These hurdles call for an iterative, participatory approach with a deep understanding of the local complexities (Garcia and Gorenflo, 1998). Siew et al. (2013) sees AR and PAR as the answer due to their collaborative nature of addressing issues concerning the community and reflecting on valuable lessons gained from the implementation and deployment of the system (Siew et al., 2013). PAR has been used in a remote community in Malaysia by Yeo et al. (2011) to learn about the local community and collaborate with them in order to deploy a telecentre. Locals were also taught ICT skills in the process. Blake (2006) on the other hand is uncertain whether AR is the solution but still sees it as an appropriate approach for investigating the situation and reflecting on the impact of the design method. Blake (2002) tried a form of AR to develop an ICT system to capture data on animal behaviour for use by semi-literate animal trackers.

## 4.3 Summary

This chapter reviewed existing literature in the fields of HCI and discussed the use of AR as a research approach as a basis for conducting field experiments to investigate whether digital maps can be understood and used by non-literate, indigenous forest communities. HCI is a multidisciplinary subject that is concerned with the design, implementation and evaluation of interactive systems by trying to understand how people interact with them in order to accomplish tasks. UCD is a philosophy of design and development framework with the focus on how the system will be understood and used by a human user. The core method is an iterative design cycle, consisting of four stages, aiming at making systems 'usable': observation, idea generation, prototyping and testing. Usability is typically characterised as the absence of frustration when interacting with a system. Usability evaluation methods are divided into two groups: analytical methods carried out by experts using specific guidelines, and empirical methods applied to study actual users.

Inclusive Design has been reviewed in this chapter as it addresses different user capability levels with the aim to design enabling devices for the whole population. Universal Usability aims for universal access and successful use by addressing three main challenges: technology variety, user diversity, and gaps in user knowledge. By addressing the special needs of non-literate, forest-dependent communities who have no background in using geographic visualisations, the aim is to lower the bar in using digital mapping tools, so that these technologies can benefit people anywhere.

HCI focuses very much on making technology fit the needs of the user but the methods to test usability do not cater for specific needs. AR utilises a circular format of progression, which is visualised as a spiral to emphasise that intermediate solutions are somewhat 'better' than previous solutions. Importantly, AR differs from HCI in three main areas, as it calls for action, recognises the role and influence of the scientist as part of the process and prioritises understanding of local context over the idea of generalisable results.

# 5 Methodology

This chapter introduces the general methodology of conducting field experiments with indigenous hunter-gatherer groups in the Republic of the Congo (RoC) in order to address the Research Questions presented in chapter 2. The applied research methodology builds on the principles of Action Research (AR), where people learn about maps at the same time as research is being conducted with the aim to facilitate positive social change. UCD methods (see section 4.1) were applied for developing and evaluating tools and methods.

All experiments were carried out in the social and geographical context as described in section 2.2. To summarise, the Congo rainforest is inhabited by various communities that rely on rainforest resources for their livelihoods. The political situation, however divides the rainforest into concessions that are leased out to mining and logging companies. As part of their contracts, social responsibility agreements, or 'cahier des charges', are made that specify obligations to the government and to socio-economic development (REM and IM-FLEG, 2008). In particular, the logging sector is in charge of development and maintenance of all local infrastructure, such as roads, schools, hospitals, etc (Lewis, 2002; Seyler et al., 2010). In order to efficiently manage their obligations, both the logging company and NGOs that function as local watchdogs of the sector showed interest in bespoke mapping technology to facilitate data collection in collaboration with forest inhabitants.

Today it is widely accepted that a project's success is not solely dependant on the used technology per se, but equally on the context within which the technology is deployed. Additionally, the success of a participatory mapping project relies on participant motivation, incentives and external factors, such as funding or political dynamics. The evaluation of these factors are beyond the scope of this thesis, which is concerned with the success of methodologies rather than project implementation. Nonetheless, for the research experiments to be carried out successfully, strong ties with local partners are vital. The support of research experiments was part of agreements with local stakeholders. They had a strong interest in using the Sapelli collector (section 2.4.2) and in return acted as facilitators for this research as well as for the research of ExCiteS members Michalis Vitos and Gillian Conquest.

The first section of this chapter offers an overview of the collaborations with local stakeholders that underpin the research methodologies used to answer both research questions. These methodologies are discussed in detail and finally an overview of the bespoke software, developed for this research, is presented. Experiment specific descriptions of methodologies concerning RQ1 can be found in chapter 6 and RQ2 is described in chapter 7.

## 5.1 Establishing Collaboration with Local Stakeholders

During the Intelligent Maps project, ExCiteS partnered up with several NGOs who expressed an interest in using the Sapelli collector to improve their monitoring practices. Following the Republic of the Congo's signing of a Voluntary Partnership Agreement (VPA) with the EU in 2010, principles on the active involvement of locals in the management of the forest concessions were set forward. As described in section 2.2.4, the legal context for forest dwelling communities has been improving as a result of such measures. Preliminary to the VPA agreement, the Independent Monitoring of Forest Law Enforcement Systems and Governance (IM-FLEG) project was established by the Ministry of Forest Economy (MEF) of the Republic of the Congo with the aim of creating methods and tools to independently monitor logging activities and improve forest governance (Forest Monitor, 2011).

Two international NGOs partnered up to implement the first phase of IM-FLEG. Resource Extraction Monitoring (REM) specialises in monitoring law enforcement and natural resource extraction, while Forests Monitor focuses on transparency and accountability of the forestry sector (REM, 2004; Forest Monitor, 2011). Governance of forest law enforcement and detection and suppression of forest infractions were the focus of their cooperation. Their work was extended in 2010 with the signing of a 3-year project funded by the European Union, allowing the NGOs to continue the implementation of the IM-FLEG while also equipping local civil society organisations with necessary skills and knowledge to conduct monitoring independent of the NGOs. Cercle d'Appui à la Gestion Durable des Forêts (CAGDF) (*Circle of Support for Sustainable Forest Management*) was one of the civil society organisations involved and would come to form the local independent forestry watchdog responsible for ensuring the implementation of the newly signed VPA in the Republic of the Congo.

In addition to the partnerships with NGOs that act as watchdogs for the forestry sector, the key intermediary of the work for this thesis was the logging company Congolaise Industrielle des Bois (CIB), which manages concessions across the regions of Sangha and Likouala in the northern part of the Republic of the Congo (figure 5.1). The Singapore-owned company is FSC-certified and has the largest dedicated social mapping team in the country. The company hires staff from local communities to act as a liaison between the company and the forest people while they are specifically responsible for ensuring the inclusion of marginalised groups. In 2006, Dr. Jerome Lewis began to collaborate with CIB aiming to enable forest people to record the location of essential forest resources. As a result of such activities, the identified resources can be removed from the cutting schedules of the logging company thereby allowing locals continuous access. The collaboration is beneficial to CIB as it involves local communities directly, thus positively affecting FSC audits. CIB also hopes to improve the efficiency and accuracy of their resources mapping which is still paper-based. Due to the outdated technology and difficulty in use, the early data collection system was not used by the company's mapping staff.

***Figure 5.1*** *Congolaise Industrielle des Bois (CIB)*

The collaboration between CIB and UCL was resumed in 2012, when the ExCiteS research group finished the first prototype of Sapelli as part of the vision of Intelligent Maps (see section 2.4.2). Besides their interest in field testing the Sapelli software, which is the research subject of Michalis Vitos, CIB also facilitated mapping exercises that form the core of this thesis and the wider vision of Intelligent Maps. In particular, the logging company's social team took responsibility of organising the mapping sessions with local communities. They introduced the researchers to the communities and acted as facilitators, translators and research assistants. CIB additionally provided accommodation in the logging town Pokola, organised all transport of the researchers to the field sites either by 4x4 or boat as well as the journeys between the international airport in Brazzaville to Pokola and back.

## 5.2 Field Visits and Methods

This section focuses on the research methodologies used during Field Visit 2 and Field Visit 3, which were devised in order to answer the Research Questions of this thesis, namely: *RQ1: How can appropriate base maps be created?* and *RQ2: Are non-literate people able to understand digital maps and basic GIS interaction?* As described in section 2.4.3, an initial scoping trip (Field Visit 1) was necessary in order to define the Research Questions and inform the research methodologies used to conduct field experiments during the two further field visits (Field Visit 2 and Field Visit 3). All visited field sites are shown in Figure 5.2 and all three trips are shows in Table 5.1. The initial field visit is presented in grey colour to indicate that, at this stage, the methodology and agenda of this thesis were not yet defined given the lack of understanding of the local context.


***Figure 5.2*** *Field sites, base map data OSM*

***Table 5.1*** *Field visits*

| | Time | Communities visited | ExCiteS delegation |
|---|---|---|---|
| Field Visit 1 (scoping mission) | 19 Apr - 3 May 2013 | Longa, Sembola, Gbagbali, Attention | Altenbuchner, Conquest, Lewis, Stevens, Vitos |
| Field Visit 2 | 12 Jan - 5 Feb 2015 | Gbagbali, Kabo, Matoto, Sembola | Altenbuchner, Conquest, Vitos |
| Field Visit 3 | 23 Nov - 14 Dec 2016 | Matoto, Sembola | Altenbuchner |

To address RQ 1, methods of map generation using low cost UAVs were evaluated for performance and feasibility when dealing with restrictions imposed by the nature of this or similar projects, namely internet access, geographic points of reference time and budget. Figure 5.3 shows an overview of map generation methodologies applied at various sites and their progression over time. The choices made regarding technical equipment and testing set-ups were informed by previous literature (see section 3.1) and are further detailed in chapter 6. In addition to answering RQ 1, the products from the map generation processes were required to carry out field experiments for addressing RQ 2. The methodologies underlying the map understanding experiments are shown in Figure 5.4. They are described in detail in chapter 7.

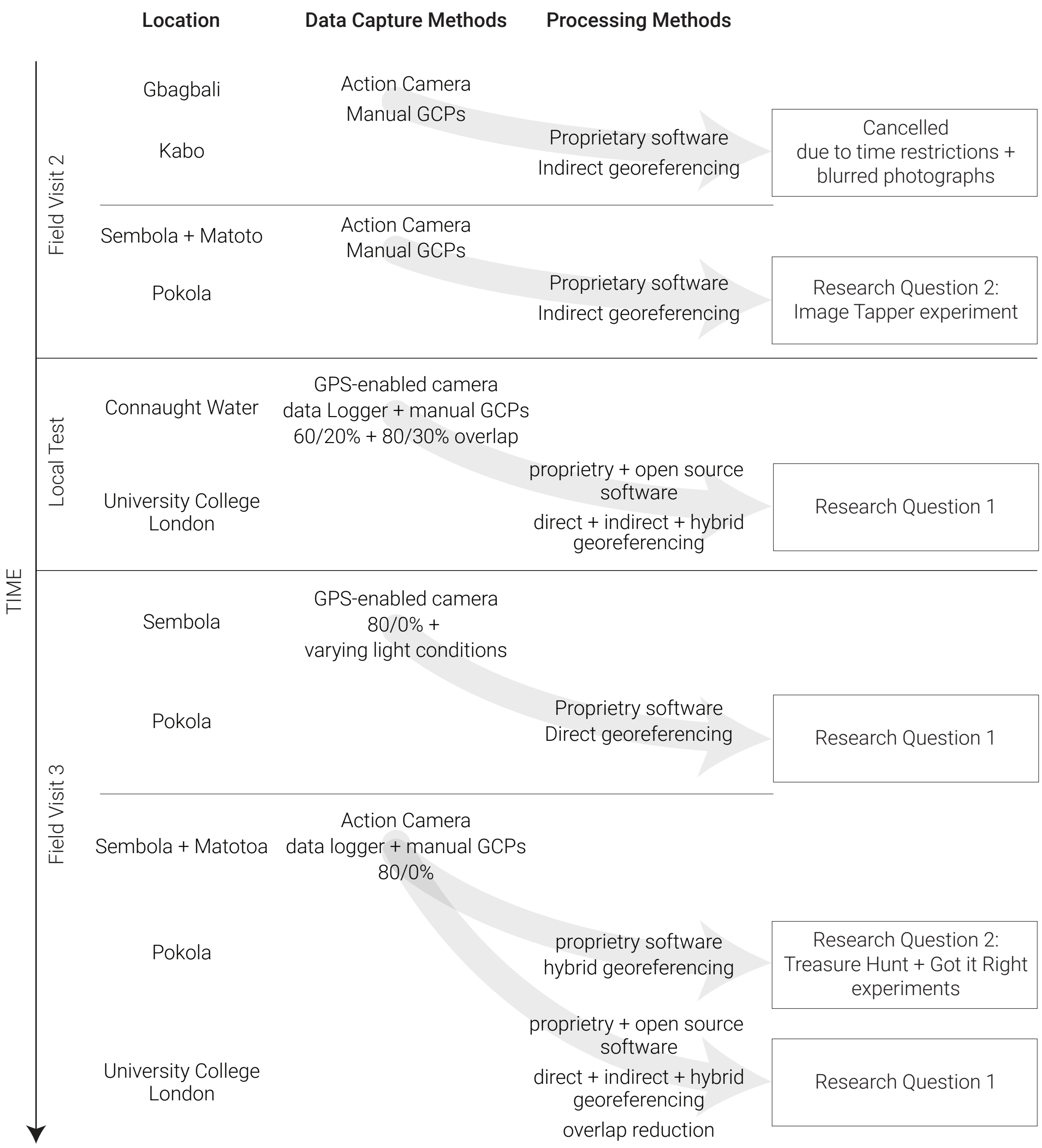



***Figure 5.3*** *Methodologies for Map Generation*

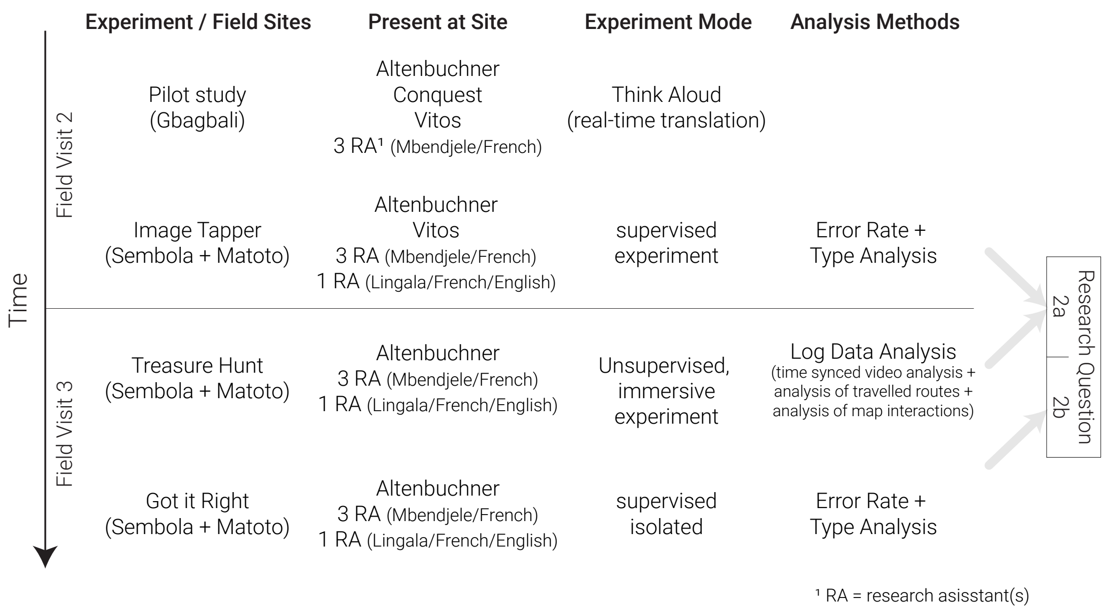



***Figure 5.4*** *Methodologies for Map Understanding*

Despite different researchers of the Intelligent Maps project being present during Field Visit 2 (see table 5.1), all design and implementation stages of the UAV mapping process were carried out single handedly by the author after CIB and local communities were informed about the process and had given their consent. A similar FPIC process as described in section 2.4.3 was carried out every time a village was visited for the first time on a specific field trip. The reason for the visit was then outlined and the community members were asked whether they are happy for the researchers to stay in order to carry out the experiments and to document the process in writing as well as in the form of photographs and videos. After having received consent, everyone was invited to register as participants. Due to the limited amount of people living in the villages, and some spending the day in the forest, it was not possible to draw a random sample of participants. Moreover, it was decided against imposing who was and was not allowed to participate for ethical reasons. Anybody could volunteer to take part in the experiments with the requirement to match the number of female with male participants. This measure was taken to avoid an over-representation of women, as they remain in the villages in larger numbers. The participants' demographics were written down by one of the research assistants. Before beginning the explanation of specific experiments, every participant was informed that they can stop at any time without the need to specify a reason. Every participant received CFA 1,000 (~ £1.35) to compensate for their time regardless of performance during the experiment. The compensations were paid at the end of each day in an open manner, so that it was obvious that nobody received more or less money than anybody else and that the amount is not to be influenced by altering the behaviour during the experiments.

### 5.2.1 Field Visit 2 Methodologies

The second field visit was a combined trip with the two ExCiteS members, Michalis Vitos (Computer Science), researching data collection tools for non-literate users, and Gillian Conquest (Anthropology), researching the impact of such projects on both the communities and researchers involved. The interdisciplinary collaboration between the researchers will be further discussed is section 8.2.4. The sites for the research specific experiments were selected in collaboration with CIB. On the one hand, the research trips had to be organised so that the usual operations of CIB were not disrupted and the sites needed to be in proximity of one hour driving or boat ride distance to a base station with electrical power, so that the research equipment (laptops, tablets, UAVs, etc.) could be charged every night. Accordingly, three different camps were identified: Gbagbali, Sembola and Matoto, shown in Figure 5.2. It has to be pointed out that the relative accessibility of these villages potentially influences the familiarity of local residents with digital technology as well as access to formal education. The lacking representation of exceedingly isolated communities is recognised as an unavoidable limitation.

UAV flight regulations (see section 8.1.3) and last minute changes to field trip schedule (see 8.2.3) were the cause that only very basic piloting of the UAV could be practiced in the United Kingdom prior to the field visit. The first aerial image capturing process using a UAV was carried out in Gbagbali, RoC. An out-of-the box solution using a wide angle action camera capable of taking photographs at short intervals was applied. The images were then processed at CIB's base in the village of Kabo. Orthophoto processing was cancelled due to insufficient time in the field as well as problems with poor quality of the images due to a scratch on the camera lens. The results of this early pilot run were not directly used but informed the further process. Two datasets were captured in the field sites Sembola and Matoto using another action camera and the same flight parameters. During the processing stage at the CIB's headquarters in Pokola, the amount of photographs were reduced to ensure that orthophotos were produced within 48 hours. The results were directly used for the map understanding experiment 'Image Tapper'.

As described in section 4.1.1, testing methods in HCI are categorised as analytical and empirical methods. Analytical methods, such as the Cognitive Walkthrough (CW) and Heuristic Evaluation (HE) require evaluators to put themselves in the position of potential users and simulate their knowledge and behaviour, while empirical methods are carried out with actual potential users. In this context, it proved impossible to identify suitable proxies to take the position of non-literate forest inhabitants with no prior exposure to technology or maps. For this reason, evaluation methods were limited to empirical methods.

Anokwa et al. (2009) and Ledlie (2010), suggest that in situations when researchers have higher social status and social power than the participants, those are especially susceptible of a specific response bias known as 'demand characteristics' (Orne, 1962). Dell et al. (2012) found that respondents are about 2.5 times more likely to prefer a technological artefact they believe to be developed by the interviewer, even when the alternative is identical. When the interviewer is a foreign researcher requiring a translator, the bias towards the interviewer's artefact increases to 5 times. In fact, the interviewer's artefact is preferred even when it is degraded to be obviously inferior to the alternative. They conclude that participant response bias should receive more attention, especially when designing for underprivileged populations. HCI4D researchers Medhi et al. (2009), who carried out her research in Bangalore slums, emphasise the importance of trust building with experiment participants by spending regular time with them prior to carrying out experiments in order to reduce the perceived superiority assigned to the researcher. However, the only way of acquiring the exclusively oral Mbendjele language is through long-term immersion with the culture and people, which was not feasible within the context of this research. The described type of bias could be observed when Vitos et al. (2017) prompted the participants to qualitatively evaluate data collector interfaces during field visit 2.

Based on that experience and literature is was decided against the method of participant interviews and instead the common HCI method Think Aloud (see section 4.1.1) was trialled to identify potential problems encountered during task completion. An initial pilot experiment was carried out in Gbagbali in which participants were asked to recognise local resources on a single aerial photograph. The Think Aloud method proved as unsuccessful due to barriers presumably related to lacking confidence but also lacking vocabulary. This finding confirms Chetty and Grinter's (2007) claim that HCI methods tend to rely on the assumption that users are familiar with technology, at least to a degree that they are able to express opinions using the terms, concepts and language associated with the particular technology in question. Those who are unfamiliar with the technical jargon, however, will find it difficult to find the words to express their needs. HCI methods are a social product of the industrialised part of the world and, as such, they have an impact on how technology design and evaluation are approached. What made things even more difficult when asking participants to point out features on an aerial photograph (or map) was the vagueness of gestures, especially in combination of the delay of real-time translation.

Through the pilot experiment it became evident that a quantifiable method was required that could evaluate understanding based on action rather than qualitative statements. The first experiment, carried out to answer RQ 2 was a form of field observation, based on computer logging. A custom app, called 'Image Tapper', was developed to present the map created using a UAV and log user interaction which could then be associated with specific tasks the participant attempted to solve. The evaluation was based on error rates and error types. The experiment was carried out in the centre of the villages where the participant sat down with the researcher and a research assistant to translate the tasks. The participants were seemingly nervous and felt under pressure to solve a task while being supervised (see figure 5.5).

***Figure 5.5*** *Supervised research experiment*

### 5.2.2 Field Visit 3 Methodologies

In preparation for Field Visit 3, systematic experiments with a GPS-enabled camera, varying amounts of image overlaps and various georeferencing methods were carried out in the United Kingdom. A local test site, Connaught Water, was identified for the experiments. The orthophotos were processed at UCL using proprietary as well as open source software. The results fed into the proposal of a systematic orthophoto procession pipeline (section 6.5) and informed the selection process of data capture and processing methods during the subsequent field visit.

The last field trip was carried out alone due to different stages of research progression. During the previous field visit the villages Sembola and Matoto proved to be suitable for carrying out experiments due to easy accessibility from Pokola, where electricity was available to charge technical equipment as described above.

Several flights were carried out in Sembola. Different image overlap scenarios were tested under the influence of varying light conditions. An unforeseen confiscation of the UAV, detailed in section 8.1.3, imposed a forced stop on these tests. When the UAV was returned, a set of photographs for each of the locations Sembola and Matoto were taken using an action camera and a GPS flight logger. Maps for both field sites were immediately processed in Pokola to be used for experiments to answer RQ2. On arrival in London, further processing was carried out on these data sets to experiment with various georeferencing and overlap combinations. The exact implementations and results of the presented methods are detailed in chapter 6.

In order to decrease the level of stress observed during the Image Tapper experiment conducted during Field Visit 2, and to allow participants to get to know the devices and digital maps on their own in a more exploratory and immersive way, the second experiment took the shape of an unsupervised Treasure Hunt organised in Sembola and Matoto. The participants were allowed to carry out the task in groups and their device interactions and GPS locations were recorded in a time-synchronised manner. Behavioural log analysis entirely replaced the method of direct observation. The great advantage of this method is a more natural and holistic representation of user interaction uninfluenced by observers Dumais et al. (2014). However, behavioural logs provide detailed information about what people are doing but give no indication as to why they are doing so and their levels of satisfaction. An explorative log data analysis was applied by reconstructing the experiment context through time synchronisation of GPS log data and interaction log data. The travelled routes extracted from GPS logs were analysed and evaluated for success and finally compared with map interaction patterns.

In order to address methodological shortcomings, right after the Treasure Hunt, a third experiment, Get it Right, was carried out, in which participants were prompted to correct resources on custom-written GIS that were either displayed in a wrong location or showing the wrong feature. Like in the Image Tapper experiment, the method was computer logging based field observation with the evaluation accounting for error rates and error types. This time the pressure was decreased through isolation from all bystanders except for the research assistant, who received intensive briefings and was encouraged to take more time to explain the procedure and increase the level of trust.

## 5.3 Software Development

In order to carry out the experiments for this research, several Android apps and Python scripts have been developed to be applied during the phases of experiment preparation, experiment execution and post-processing. Table 5.2 provides an overview of all bespoke software along with a short description, while a detailed explanation will be provided in the referenced sections. All code referenced in this table can be found in the Appendix A.5.

***Table 5.2*** *Bespoke software*

| Name | Description | Section | Third-party code |
|---|---|---|---|
| Flight planner | Calculates flight parameters to obtain specific endlap/sidelap combinations | 6.1.2 | – |
| FPV2KML | Decodes proprietary FPV file format and convert it into KML format | 6.1.3 | Geosync (Racicot et al., 2014), SimpleKML (Lancaster, 2016) |
| Image Tapper App | Records coordinates of tapped map locations | 7.1.1 | Subsampling Scale Image View (Morrissey, 2016) |
| Coordinate viewer | Performs coordinate system transformations to view all points in same reference system | 7.1.3 | – |
| Voronoi generator | Produces semi-transparent Voronoi diagrams in relation to treasure locations | 7.1.3 | – |
| Treasure Hunt App | Facilitates Treasure Hunt game with configurable treasure constellations shown on a map and all movements and interactions being tracked | 7.2.1 | ArcGIS SDK (ESRI, 2017), SimpleFileDialog (Works, 2013) |
| Route calculator | Calculates routes based on a network for given treasure constellations producing shortest overall route and nearest unvisited treasure rules | 7.2.3 | – |
| Got it Right App | Facilitates basic GIS interaction enabling participants to modify the location or the value of a given data point | 7.3.1 | ArcGIS SDK (ESRI, 2017), SimpleFileDialog (Works, 2013) |

## 5.4 Summary

This chapter gave an overview of the development and adaptations of the research methods to take into consideration the local environment as well as the participants' requirements. The collaboration with local stakeholder CIB made it possible to conduct user research with local forest communities as part of the UCL ExCiteS research group. Two field visits were necessary to generate maps and carry out the mapping experiments in order to answer the two Research Questions, each one detailed individually in the upcoming chapters. The research objectives addressed by each experiment are presented in table 5.3.

*Table 5.3* *Objectives and experiments*

| Objective | Experiments |
| --- | --- |
| Chapter 6 – Research Question 1: *How can appropriate base maps be created?* | |
| Feasibility evaluation of offline, decentralised and affordable map creation using UAVs | Testing of<br>• camera<br>• overlap<br>• geo-referencing<br>• processing software set-ups |
| Chapter 7 – Research Question 2: *Are non-literate people able to understand digital maps and basic GIS interaction?* | |
| *RQ 2a: Are non-literate hunter-gatherers able read maps?* | |
| Evaluation of base map understanding in relation to own location and environment | Image Tapper experiment<br>• Tap on known locations on digital orthoimage |
| Evaluation of understanding abstract symbology as location marker | Treasure Hunt experiment<br>• Find locations marked on digital orthomap |
| *RQ 2b: Are non-literate hunter-gatherers able contribute to maps?* | |
| Evaluation of performing location and feature editing in GIS | Got it Right experiment<br>• Correct incorrect location or feature classifications |

# 6 Maps from Aerial Imagery

The identification or generation of suitable reference maps is essential for the creation of mapping tools that allow hunter-gatherers in the Congo Basin to actively participate in GIS based decision-making processes. An initial investigation of available maps and data, discussed in section 2.3.2, revealed that existing products are unsuitable for the purpose of this research, due to insufficient spatial and temporal resolution of existing maps and satellite imagery, cloud cover and/or high costs of acquisition. Literature (see section 3.1.1) shows that the restrictions of cloud cover, spatial resolution, and price can be overcome by deriving orthophoto maps from aerial photographs taken at low altitudes, which guarantees a high-level of detail as well as a cloud-free result.

This chapter addresses the Research Question: *How can appropriate base maps be created?* (see section 2.5). The approach taken is to explore the generation of maps from aerial imagery using low cost UAVs and evaluate the feasibility when dealing with restrictions imposed by the nature of this or similar projects, namely internet access, geographic points of reference time and budget. The first section discusses the choices of technical equipment as well as the implementation of various testing set-ups for the project. Subsequently, the testing scenarios and results will be demonstrated and discussed before proposing a suitable set-up and processing pipeline that does not rely on internet access, existing maps or other geographic information such defined coordinates.

## 6.1 Equipment and Testing Set-Up

According to the adaptable variables that influence the result of the orthophoto map generation (see section 3.1) this section is subdivided into the themes shown in the overview figure 6.1: UAV & camera, mission planning, georeferencing and image processing. For each of these themes, different equipment or configurations have been tested, which are presented in the relevant boxes. These will be introduced in this section and will be picked up again in the results section 6.3 to demonstrate the experiment outcomes.

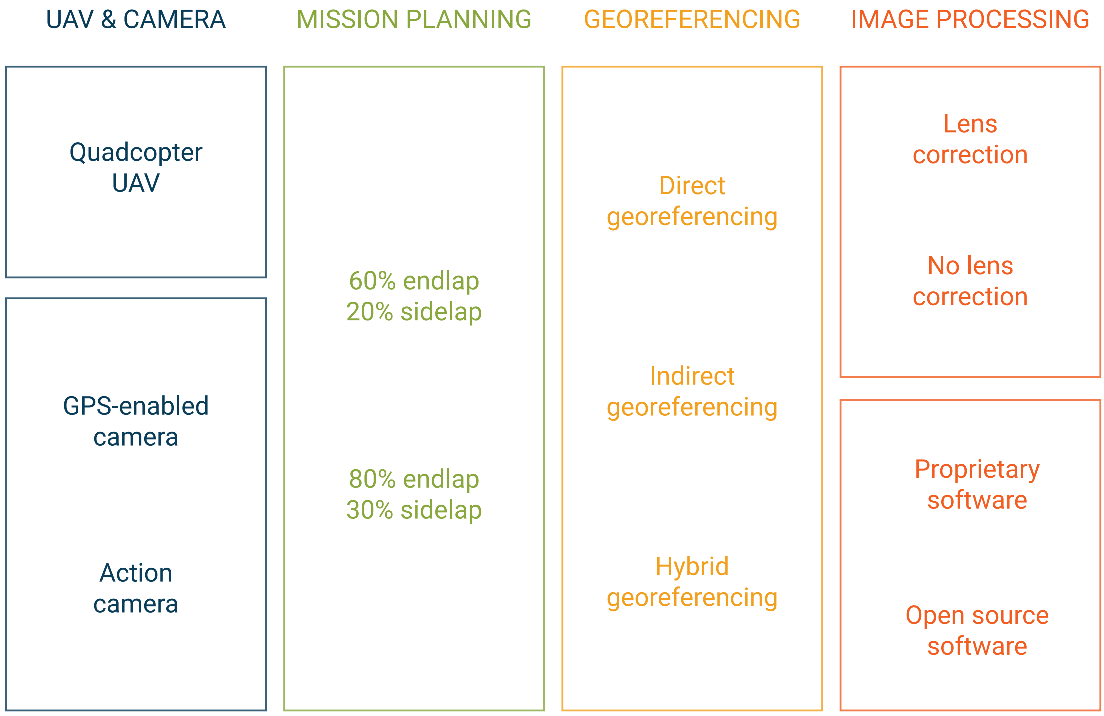



***Figure 6.1*** *Tested equipment & configurations*

### 6.1.1 UAV & Camera

In choosing the appropriate UAV for the project in December 2014, the factors of portability, affordability, ease of piloting as well as the possibility to fully automate the flight process were taken into consideration. Given the advanced piloting requirements and limited manoeuvrability of fixed-wing aircrafts, the decision was made to acquire a multi-rotor UAV. The autopilot capabilities and comparably low price of the DJI Phantom 2 quadcopter made the model a suitable choice (figure 6.2), which was reinforced by its popularity (see section 3.1.1). The unit, combined with a Zenmuse H3-3D gimbal to fit a GoPro camera and two spare batteries, came at a cost of £707. A gimbal keeps the camera in a horizontal position regardless of the aircraft's movements. Controlling the UAV is simple and feasible for first-time users due to its inbuilt position holding and stable hovering capabilities. The quadcopter includes a 2.4 GHz handheld radio controller that is coupled to the aircraft and has a range of up to 1 kilometre line-of-sight. In the event of losing connection to the controller when the battery charge falls below a critical point, the UAV automatically returns and lands at the take off location. Furthermore, the unit is equipped with an integrated GPS auto-pilot system to carry out automated flights according to pre-programmed paths, which are further discussed in the following section 6.1.2. Table 6.1 provides an overview of the technical specifications of the UAV.

***Figure 6.2*** *DJI Phantom 2 (DJI, 2017c)*

***Table 6.1*** *DJI Phantom 2 specifications (DJI, 2017c)*

| | |
|---|---|
| Weight (Battery & Propellers included) | 1000g |
| Hover Accuracy (Ready to Fly) | Vertical: 0.8m; Horizontal: 2.5m |
| Max Yaw Angular Velocity | 200°/s |
| Max Tilt Angle | 35° |
| Max Ascent / Descent Speed | Ascent: 6m/s; Descent: 2m/s |
| Max Flight Speed | 15m/s (Not Recommended) |
| Diagonal Length | 350mm |
| Flight Time | 25mins |
| Take-off Weight | $\leq$1300g |
| Operating Temperature | -10°C $\sim$ 50°C |
| Communication Distance (open area) | 1000m |

Having reviewed the specifications of digital cameras available on the market at the time, the GoPro Silver Hero 4 (figure 6.3a) and the Canon PowerShot SX260 HS (figure 6.3b), were selected for testing their suitability for aerial mapping. Both devices are consumer grade digital cameras available for under £300 (GoPro) and £200 (Canon) at the time of purchase. Each comes with several advantageous and disadvantageous features in regard to their use in aerial mapping. The technical specifications are detailed in table 6.2.


***(a)*** *GoPro Silver Hero 4* ***(b)*** *Canon PowerShot SX260 HS*

***Figure 6.3*** *Cameras*

***Table 6.2*** *Camera specifications*

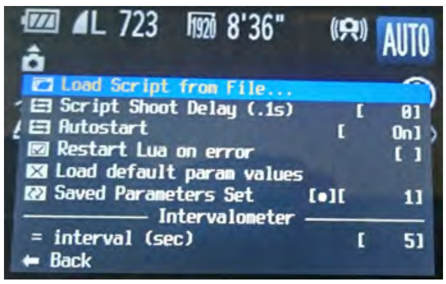
| | GoPro Silver Hero 4 | Canon PowerShot SX260 HS |
|---|---|---|
| Dimensions (W x H x D) | 41 x 59 x 21 mm | 106 x 61 x 33 mm |
| Weight (incl. battery) | 83 g | 231 g |
| Effective photo resolution | 12.0 MP | 12.1 MP |
| Photo dimensions | 4000 x 3000 | 4000 x 3000 |
| Focal length | *not specified* | 4.5 mm |
| Sensor dimensions (W x H) | *not specified* | 6.17 x 4.55 mm |
| Shockproof + Waterproof | Yes | No |
| GPS receiver | No | Yes |
| Distortion | Barrel distortion | None |
| Time lapse interval (sec) | 0.5, 1, 2, 5, 10, 30, 60 | None |
| Camera mount | 3-axis gimbal | None |

The GoPro has the advantage of being fully compatible with the DJI Phantom 2. The UAV was shipped together with the Zenmuse H3-3D, which is a gimbal compatible with DJI flight control systems. While the tilt angle can be adjusted through the radio controller, the 3-axis stabilisation mechanism makes sure that the camera stays in a fixed position even when the UAV itself tilts in either roll, pitch or yaw direction (figure 6.4). The GoPro falls into the category of action cameras, which are small and light as well as shockproof and waterproof. The GoPro supports high resolutions of up to 12MP and covers a wide angle enabled by the fish-eye lens. While this is advantageous for the purpose of filming action scenes with the main subject in the centre of the scene, the 'barrel' effect caused by the lens type has the characteristics of vertical and horizontal straight lines appearing as convex curves. This poses a problem to the process of producing a geometrically accurate, orthographic map. This issue is taken into consideration and handled in the image processing stage by reversing the barrel effect and cropping the resulting artefacts at the edges of the images (see section 6.1.4).

***Figure 6.4*** *Zenmuse H3-3D gimbal (DJI, 2017d)*

As a second camera set-up, the Canon PowerShot SX260 HS was chosen, which is equipped with an on-board GPS receiver to automatically 'geotag' the taken photographs with a geographical location. Given the lack of known Ground Control Points (GCPs) in the Republic of the Congo, direct georeferencing provides an opportunity to obtain absolute reference during orthophoto generation (see section 3.1.2). With 12.1 megapixels, the camera achieves similar resolution as the GoPro without the problems connected with the fish-eye distortion. However, with 231g compared to 83g, the Canon is significantly heavier than the GoPro, which potentially reduces flight time due to higher power consumption. Furthermore, it is missing the continuous shot functionality, which is essential for aerial mapping. This limitation can be overcome by loading the Canon Hack Development Kit (CHDK) using the camera's SD card. CHDK is an open source firmware package that enables the camera to run custom scripts, such as the Countdown Intervalometer by Hazelden (2010). This allows the user to set a time interval at which the camera shutter gets automatically triggered. The DJI Phantom does not come with a camera mount for the Canon PowerShot SX260 HS and, therefore, a generic user-designed 3D printed mount was ordered from the online store (Shapeways, 2015) and fitted to the UAV.

***(a)*** *Camera mount (Shapeways, 2015)*




***(b)*** *CHDK Intervalometer*

***Figure 6.5*** *Modifications for Canon PowerShot SX260 HS*

Figure 6.5 shows the modifications made to use the Canon PowerShot camera for UAV-borne photogrammetry purposes. Despite the possibility to attach the camera to the UAV using the camera mount shown in figure 6.5a, there is no stabilisation against roll, pitch and yaw effects (see section 3.1.2). Figure 6.5b shows the camera's UI when booting into the custom CHDK firmware and loading the Intervalometer script from a file. In combination with parameters such as flight speed and altitude, the defined time interval plays a crucial role when planning the desired overlap between consecutive photographs.

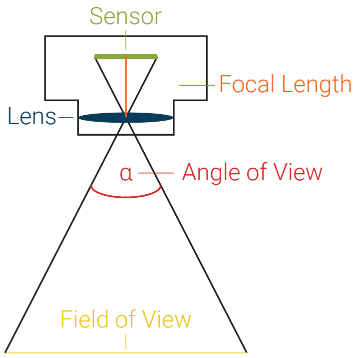
### 6.1.2 Mission Planning

The literature states that orthophoto generation from aerial photography requires a forward overlap, known as endlap, of 60 - 80% and a side overlap, or sidelap, of 20 - 30% (see

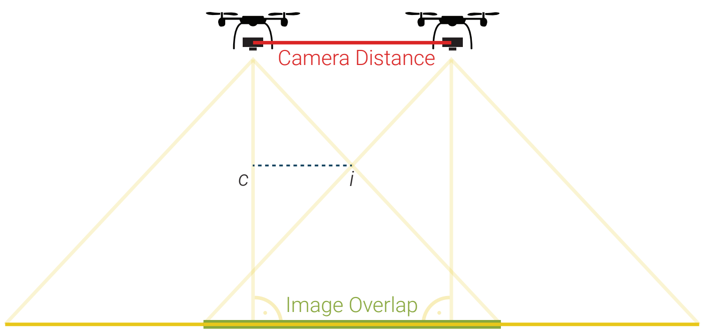
3.1.1). The parameters to influence the amount of endlap and sidelap are the viewing angle of the camera, the altitude and speed of the UAV, as well as the time interval at which photos are taken. For the purpose of this research, a Python script was written to calculate the required endlap and sidelap values using the approach explained in this section (see Appendix A.5).

In digital photography, the image sensor replaces the film used in analogue photography to capture and convert light rays into an image. The focal length describes the distance in millimetres between the rear of the lens and the image sensor when the lens is focused at infinity. The image sensor dimensions combined with the focal length define a camera's angle of view (see figure 6.6a). The angle of view together with the altitude define the Field of View (FOV), which is the extent of the world captured in a photograph (Bourke, 2003).

To calculate the angle of view $\alpha$, given the sensor dimension $s$ and the focal length $f$, the formula is $\alpha = 2\arctan\frac{s}{2f}$. To obtain the angle in both dimensions, the calculation is to be carried out for both sensor width and sensor height. Given the altitude $h$ and the angle of view $\alpha$, the FOV is calculated using the formula $FOV = 2h\tan\frac{\alpha}{2}$.



***(a)** Angle of View*



***(b)** Camera distance*

***Figure 6.6*** *Flight parameter calculations*

Once the FOV has been obtained, the flight speed and distance between two strips are calculated to achieve a specific endlap/sidelap combination. Figure 6.6b shows the relationship between FOV, image overlap and camera distance. The camera distance in between two shots equals the horizontal distance between the initial camera position $c$ and the point of FOV intersection $i$, multiplied by 2. The function to compute the camera distance, as shown in listing 1, requires the FOV and image overlap defined as a fraction of the FOV. First, the distance to the point of FOV intersection is computed (line 2), followed by the distance to the camera position (line 3). The difference of both multiplied by 2 makes up the required distance between photo shots to achieve a specified overlap (line 4).

**Listing 1** Camera distance function

```
def get_camera_distance(fov, overlap):
    distance_i = fov - (overlap * fov / 2)
    distance_c = fov / 2
    return (distance_i - distance_c) * 2
```

If the camera is mounted to the UAV with the sensor width perpendicular to the flight direction, the distance between two flight strips is directly calculated by passing the width of the FOV along with the desired sidelap fraction to the function described in listing 1.

Passing the height value of the FOV along with the desired endlap fraction to the function returns the distance between shots in the direction of flight. This distance is defined by the speed in which the camera travels as well as the time interval between shots. The formula $speed = \frac{distance}{time}$ is applied to obtain the required flight speed in regards to the set interval in which photographs are taken.

Once the parameters have been calculated, the flight path must be programmed and uploaded to the UAV's flight controller for autopilot mode. For this to work, a 2.4G Bluetooth Datalink (DJI, 2017a) is required as well as the DJI GroundStation app (DJI, 2017b), which is compatible with iPad (iOS 6.1 or above). Alternatively, a Windows based desktop application can be used for flight mission programming and uploading. A software review revealed that the Windows application was more complicated to use than the lightweight iOS app. To ensure ease of use and portability, the decision was made to purchase a second-hand iPad mini 2 for flight mission upload. The data link consists of an air transceiver unit to be installed on the aircraft and plugged into the flight control system and an externally powered ground transceiver unit connecting to the GroundStation app via bluetooth. Figure 6.7 shows the ground segment for automatic flight upload and execution. The flight controller, shown in figure 6.7a, needs to be switched on so that the app can connect to the aircraft via the bluetooth link, powered by an external battery.

A close up view of the GroundStation app is shown in figure 6.7b. If an internet connection is available, the GroundStation app provides a Google satellite and street map as reference to set the locations of way point markers through drag and drop interaction. In situations with no internet access, as in the context of this project, latitude/longitude coordinates can be manually entered to set way points. Predefined, adjustable flight patterns are available, such as the grid, which is typically used for the purpose of orthophoto generation. Once the setting and adjusting of way points are finalised, aircraft speed and altitude can be set. Tapping the 'Go' button will upload all settings to the UAV's flight controller and start the automatic take off and flight execution. The location of each way point can be modified at any time provided the aircraft is in reach of bluetooth connection.

***(a)*** *Autopilot set-up* ***(b)*** *GroundStation app*

***Figure 6.7*** *Autopilot ground equipment*

### 6.1.3 Georeferencing

As discussed in section 3.1.2, there is a distinction between direct and manual georeferencing. The first approach makes use of coordinates information of geotagged photographs, while the latter approach requires a list of Ground Control Points (GCPs). Literature states that, depending on the quality and distribution of GCPs, manual georeferencing has the potential to produce more accurate results than direct georeferencing (Carrivick et al., 2016). The absence of accurate, absolute reference points in countries such as the RoC as well as the absence of professional photogrammetry equipment to achieve accurate GPS readings poses a challenge to manual referencing in this project. Furthermore, it is challenging to identify enough well distributed GCP in areas covered with dense rainforest due to limited visibility of the ground. In this research, three different set-ups of producing georeferenced orthophotos under given circumstances are tested: manual georeferencing using a Garmin GPS 60 device, direct georeferencing using the camera's GPS receiver and direct georeferencing using the UAV's GPS receiver.

The aircraft's inbuilt GPS module sits directly underneath the top shell (see figure 6.8a) for optimal exposure to satellite signals. The GPS readings are consumed by the flight controller for automatic flight execution as well as safety control. There is, however, no connection with the camera, which is externally attached to the bottom of the UAV, so it is not possible to directly geotag photographs with the UAV's GPS readings. Furthermore, there is no functionality to log parameters, such as geographic coordinates, during flight execution. To overcome this shortcoming, the company Flytrex developed a data logger, called Flytrex Core V2, that reads data through a wired connection to the UAV's GPS receiver.

In order to geotag photographs with location readings taken by the UAV's GPS module, the Flytrex Core V2 module was installed on the aircraft. The data logger produces and stores log files that were then used to geotag the taken photographs through time synchronisation. It was installed by opening the top of the Phantom 2, disconnecting the GPS receiver from the flight controller and connecting the Flytrex Core V2 via cable to both. The cable was subsequently threaded through a hole in the shell and the chip itself was fixed to the outside of the aircraft via tape (figure 6.8b). Flight parameters are recorded and saved to a microSD card as log files in the company's proprietary file format FPV. These binary files can be uploaded to the company's online platform where one can share flights with an online community, if desired. From there, the user is given the possibility to export the uploaded file in the standard file formats Comma Separated Values (CSV) and Keyhole Markup Language (KML).

***(a)*** *GPS module* ***(b)*** *Flytrex module*

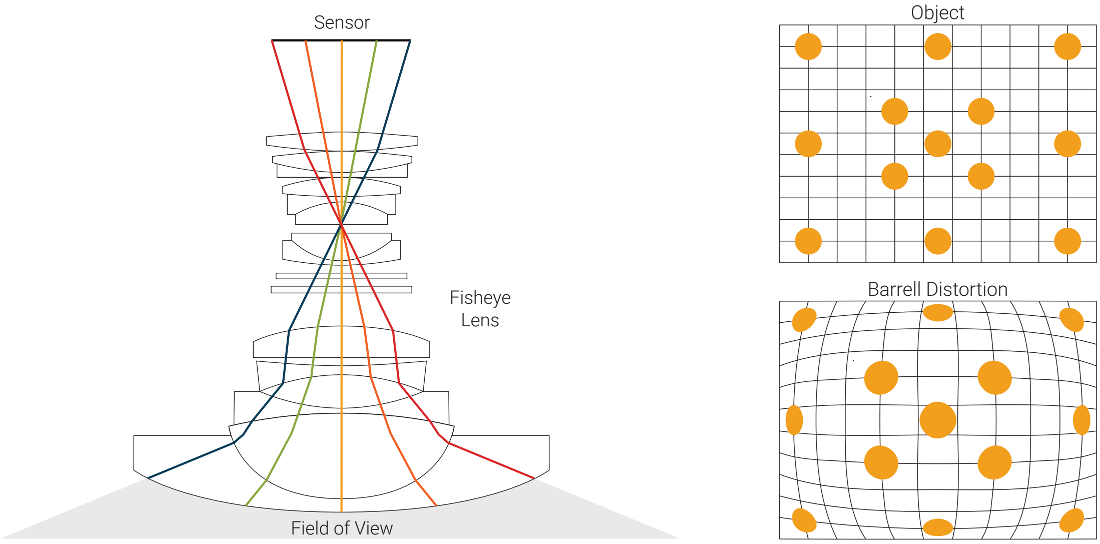
***Figure 6.8*** *Flytrex Core V2 installation*

For this approach to be viable in a disconnected scenario, the entire processing chain must work without the need of an internet connection. In late 2014, an open-source Python project called Geosync (Racicot et al., 2014) was initiated with the aim to georeference aerial photographs by synchronising and interpolating image time stamps with GPS track time stamps. The project has not been maintained since March 2015. While the outlined vision has not been fully realised, the project contains a working script to successfully decode the binary FPV format, which was used to implement the solution described here.

Given the requirement to process all data without the need of an internet connection, a Python script was written to read in the proprietary FPV file, decode it using the GeoSync decoder and convert it into a KML format holding longitude, latitude and altitude as well as time stamp information in the form of KML Placemarks. The Python script can be found in Appendix A.5. Subsequently, the KML file and the photographs are loaded into GeoSetter, a freeware by Schmidt (2011) that allows to update the photographs' location information through time synchronisation with a KML track file.

### 6.1.4 Image Processing

As described above, photographs taken with a GoPro camera appear distorted due to the fish eye lens (figure 6.9). A schematic example of such a lens, after Sun (2016), is shown in figure 6.9a. The fish eye lens it characterised by its extremely wide angle, whereby the proportions of the scene to be captured are radially distorted in order to achieve the large field of view. This results in a barrel distortion, where all straight lines in the photograph are arched outwards, as illustrated in figure 6.9b. The distortion exaggerates towards the edges of the image with only the centre being perceived by the human eye to be correctly displayed (Parrish and Jacobs, 2012).




***(a)*** *Fish eye Lens (Sun, 2016)* ***(b)*** *Distortion*

***Figure 6.9*** *Fish-eye lens effects*

An example of a photograph taken with a GoPro camera is shown in figure 6.10a. In order to correct for the barrel effect, the program PTLens by Niemann (2017) was utilised. Figure 6.10b shows a geometrically corrected version of the same photograph. The correction, however, comes at the cost of reducing the size of the FOV, which is clearly visible when regarding the footpath on the right in both photographs shown in figure 6.10. Niemann (2017) pioneered in creating the first application to automate distortion correction in 2002. Since then, several photo editing software providers, including Adobe Photoshop, have included lens correction features in their products. In this project, PTLens v9.0 is used due to its simplicity and its low price of $25 (~£19) per license.

***(a)*** *Raw photograph* ***(b)*** *Corrected & cropped photograph*

***Figure 6.10*** *Fish-eye distortion*

The state-of-the art approach to convert photographs, taken with a UAV, into an orthographic map is a Structure from Motion (SfM) processing pipeline, as discussed in section 3.1.2. A number of software packages are available that implement the various processing steps required in SfM. Table 6.3 provides an overview of such software categorised by the provided features, the platform they run on and the occurring costs when purchasing the software or a service. The list is not comprehensive, but includes popular representatives of each of the three prevalent software distribution models: commercial, open source and software as a service.

***Table 6.3*** *Image processing software*

| | Features | Platform | Price |
|---|---|---|---|
| Pix4D | SfM tool chain | Windows, Linux, macOS (in beta) | Educational: £1308<br>Commercial: £5670* |
| PhotoScan | SfM tool chain | Windows, Linux, macOS | Educational: £429<br>Commercial: £2731* |
| Drone2Map | SfM tool chain | Windows | £1171 per year* |
| OpenDroneMap | SfM tool chain | Linux | free |
| MapKnitter | Manual image stitching | Web service | free |
| Drone Mapper | SfM as a service | Web service | quote based |
| Maps Made Easy | SfM as a service | Web service | £0.05 - £0.17 per acre* |

* Converted into Pound Sterling according to current rate.

Proprietary, commercial software with advanced graphical user interfaces typically come at a high cost but provide sophisticated, out-of-the-box solutions while offering support and maintenance. In order to maintain their position in the market, they utilise a 'black box' approach meaning that the exact implementation of algorithms remains a secret. Licenses can be bought per installation or as a monthly or yearly subscription. Popular image processing programs in this category are PhotoScan, Pix4D and Drone2Map. While the first two have dominated the market since 2010/11, Drone2Map was launched in 2016 as ESRI's recent addition to their mapping suite. However, it is fully built on Pix4D's photogrammetry engine (ESRI, 2017), which means that there is no difference in performance or output quality between the two. Drone2Map is a seamless integration with ESRI's ArcGIS but is limited to Windows platforms. Furthermore, they offer varying pricing models, which are both considerably more expensive than their competitor Agisoft PhotoScan.

Open source projects, such as OpenDroneMap and MapKnitter, offer alternatives to the proprietary software. The programs are free to use or modify but often at the cost of user-friendliness. OpenDroneMap, for instance, requires the user to operate the software using command line tools. Fixing of software bugs and other maintenance as well as feature requests are dependent on the willingness and availability of volunteer developers who often work on such projects in their spare time. MapKnitter, as opposed to all other software discussed here, does not offer a full SfM workflow but assists in manual stitching by providing a web browser based Graphical User Interface (GUI) and a backdrop satellite map as a reference. All user generated maps are licensed under a creative commons licence resulting in the map creator losing the exclusive rights to the product.

A third option is the Software as a Service approach, which requires the user to upload their images to a web server where all of the processing takes place. The costs depend on the chosen service as well as the size and quality of the final product. DroneMapper and Maps Made Easy are listed here due to their popularity, however, many more providers of such services exist.

For this research, it is important that all processing can be carried out in the field, without the need of accessing online services. Thus, all web service options were eliminated when choosing appropriate tools. Due to the argument of increased reliability over open source software, the decision was made to purchase a proprietary license for Agisoft PhotoScan to process data in the field. This decision was further based on its good reputation amongst internet users and the relative low price compared to its competitor Pix4D. Drone2Map was not available at the time of the field trip in early 2015. All field processing has been carried out with PhotoScan. On return to the UK, images were also processed with OpenDroneMap to evaluate both systems as well as the quality of the generated outputs.

**Agisoft PhotoScan**

PhotoScan is a proprietary software created by the company Agisoft LLC based in Russia. It runs on Windows, Linux and iOS and provides a user friendly GUI to generate orthophotos from image files in five steps. The company promises successful reconstruction from arbitrary images given that the reconstructed points are visible on a minimum of two photographs (Agisoft LLC, 2017a). The implemented SfM algorithms estimate the internal parameters of the cameras and carry out a camera alignment as a first step. The software identifies and matches common points on the provided photographs while estimating and refining the camera positions. The second step is to build a dense point cloud based on the estimated camera positions. Third, the software reconstructs a three-dimensional mesh based on the dense point cloud. Finally, the mesh is textured and used for ortho-rectification. The user can set various input parameters for this workflow and intervene between each of the steps to manually add or remove camera positions.

The software itself does not limit the number of images used in the reconstruction but the processing time increases with the amount of photographs. Verhoeven (2011) points out that fast geometry reconstruction mode is limited to 1024 photographs. Agisoft LLC (2017b) specify that in the majority of cases, the limiting factor in processing large projects is the amount of available RAM. The most resource heavy operation is the reconstruction of geometry (dense cloud and mesh generation). In order to process 1000 photographs in high quality, the approximate memory consumption is estimated at 16GB RAM (Agisoft LLC, 2017b). Furthermore, the company recommends high speed multi core CPU (3GHz+) as well as high-end OpenCL or CUDA-compatible graphics card to speed up processing time.

**OpenDroneMap**

OpenDroneMap is a free and open data processing tool chain specifically targeted at civilian UAV imagery. Similar to PhotoScan, it provides a full SfM tool chain from camera alignment to ortho-rectification. OpenDroneMap is a command line tool running on Linux. At the time of writing, the developers are working on a web interface to make its use easier for people unfamiliar with the command line. One of the long-term goals of OpenDroneMap creators is to optionally push resulting data to open online repositories. Unlike proprietary software algorithms, all used source code and calculations are known and open for anyone to contribute to. OpenDroneMap extends OpenSfM (Mapillary, 2013) for camera alignment, which is based in the Computer Vision library OpenCV. After the generation of tie points and image alignment, the toolchain implements an algorithm by Shen (2013), to create depth maps for each image and subsequently merge them into a single, dense point cloud. To create the mesh, a Poisson Surface Reconstruction algorithm (Bolitho et al., 2009) is applied. Multi-View Stereo used for texturing the mesh output is described by Waechter et al.

(2014). For georeferencing, the software extracts Exchangeable Image File Format (EXIF) or GCP data and converts into UTM coordinates before they are applied to geo-rectify the point cloud, mesh or textured mesh. OpenDroneMap does not further specify any hardware requirements, other than the need of a native Linux environment or a virtual machine running Ubuntu 14 or higher.

## 6.2 Field and Test Site Deployments

This section provides an overview of the used methods, equipment and configurations during two field trials and one local trial. Prior to the field visits to the Republic of the Congo, the host company CIB was informed about the use of a UAV and they were assisting with official procedures as further detailed in section 8.1.3. When arriving at a field site, a FPIC process was carried out with the local residents, as described in section 5.2. During this process, the function of the UAV was explained along with the plan and purpose of the research, before asking the local residents for permission to perform the flights. At this stage the UAV, referred to as 'little helicopter', was shown to the community members and it was explained that it would fly above the canopy in a grid like pattern while taking photographs that were used to create a map of their village. In each case, free and prior consent was given as people were anticipating the UAV flights with curiosity.

A forest clearing was required for take off and landing in order to elevate the aircraft above the tree canopy, for which reason the starting/landing position was chosen to be the centre of the villages. First, the aircraft was placed at the desired take off spot so that the position could be picked up by the GroundStation app through a bluetooth connection. Given the missing backdrop map in the field, the flight pattern could be entered using the indicated aircraft position along with the desired distances/directions, speed and height.

***(a)*** *Camera check* ***(b)*** *Take off* ***(c)*** *Landing*

***Figure 6.11*** *Flight execution*

Figure 6.11 illustrates the execution of a flight in the field site of Gbagbali. Once a bluetooth connection had been established between the aircraft and the ground segment and the flight path and parameters were programmed, the camera was set to take continuous shots, as shown in figure 6.11a. Next, the automatic take off (figure 6.11b) was initiated by pressing the GO button in the app, triggering autopilot flight execution. Once the flight pattern finished, the aircraft needed to be landed manually (figure 6.11c).

All flights were carried out in presence of the local populations and strictly after the concept has been thoroughly explained and the consent of the residents has been obtained. It is worth reflecting on the reactions many of the locals had when they first saw the UAV in action. The most common emotion was excitement. Some of the children, as an initial reaction, ran away from the aircraft but usually they were curious enough to turn back to the scene in order to follow the flight path for a while. Whenever the aircraft came close again, which happened several times during one flight due to the grid-like pattern, the buzz sound caused by the rotating propellers and air resistance, got louder. This noise seemed to be a great source of enjoyment for children and adults alike. When the resulting maps were shown to the population and they talked about it amongst each other they often imitated the buzz sound again. This shows that they made the connection between the UAV flights and the resulting map. Despite the residents' curiosity and close observation of all steps carried out in regards to flight execution, they did not seem to want to get actively involved in any of the steps, presumably they did not feel confident enough to do so. With more time in the field and training it could be potentially possible to include the residents more in both flight design and execution.

***Table 6.4*** *UAV flights*

| | Site | Camera | Flights |
|---|---|---|---|
| Field trial RoC 1 | Gbagbali | GoPro | 4 |
| | Sembola | GoPro | 4 |
| | Matoto | GoPro | 3 |
| Local field trial | Connaught Water | Canon | 4 |
| Field trial RoC 2 | Sembola | Canon | 5 |
| | Matoto | GoPro | 3 |
| | Sembola | GoPro | 4 |

For the purpose of this research, a total of 27 UAV flights, presented in table 6.4, were completed with the purpose of capturing images for orthophoto map creation. Each of the flights was performed using a DJI Phantom 2 UAV executing a pre-programmed flight path, as described in the previous section. The maps generated from these trials were shown to the residents on a subsequent visit in order to carry out map understanding experiments, detailed in chapter 7.

### 6.2.1 First Field Trial in the Republic of the Congo

This section describes field test 1, which was carried out during the second field visit, given the first visit was used as a scoping mission without any testing being carried out (see table 5.1). Due to unforeseen changes in the schedule of the project partner and host company CIB, this field visit had to be carried out earlier than planned and was executed only days after the UAV and autopilot equipment had been delivered. Little preparation could be done before the first flights were carried out in the field site of Gbagbali. A grid-like flight pattern was chosen to maximise the area while allowing for regular sidelap. Due to limited battery power, four flights were carried out at each test site with a pre-programmed flight path covering a square of 300 metres length. At a flying height of 50 metres, the camera took one photo every two metres, resulting in a data set of 1840 photographs.

Processing of photographs was immediately initiated but was not finished when leaving the field site 2 days later. In addition, the inspection of the captured images revealed that the images were blurred in the centre due to a scratch on the lens of the GoPro camera, caused by an earlier aircraft crash. For these reasons, the decision was made to use a single photograph for a pilot map reading experiment with the residents of Gbagbali, discussed in section 7.1, and exclude the dataset from further investigations concerning orthophoto creation, due to blurred images. The image alignment could, however, be successfully executed, indicating a sufficient endlap/sidelap combination. Thus, two further datasets were captured with the same flight parameters, shown in table 6.5, in the field sites Sembola and Matoto, factoring in more time for image processing.

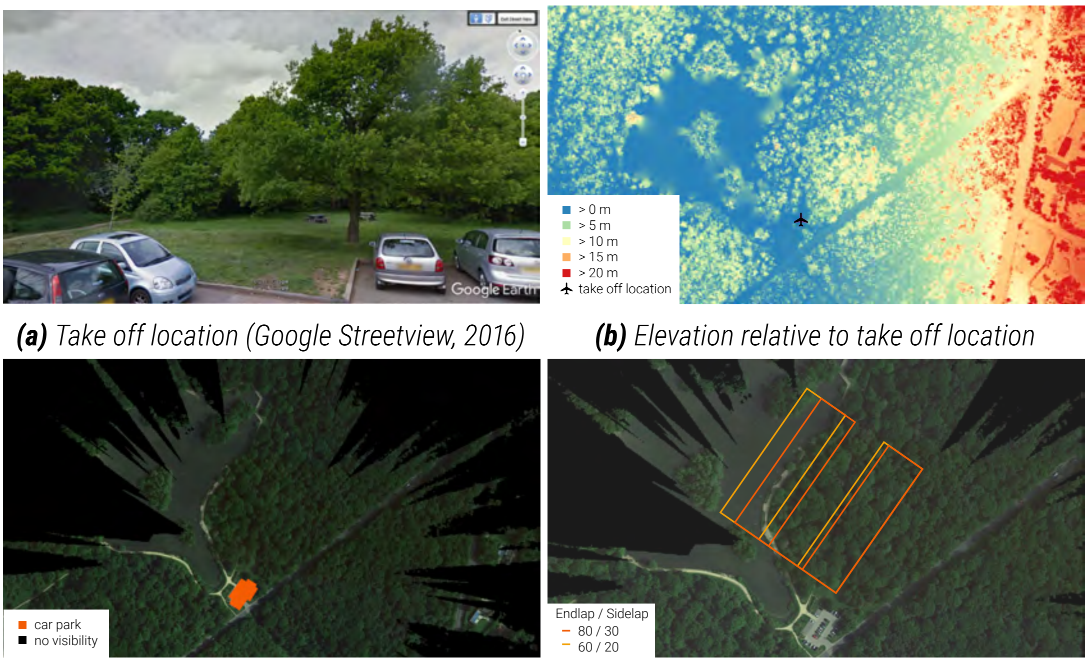
***Table 6.5*** *Field trial 1 – flight parameters*

| Village | Gbagbali | Sembola | Matoto |
|---|---|---|---|
| Flights | 4 | 4 | 3 |
| Camera model | | GoPro Hero4 Silver | |
| Altitude | | 50m | |
| Image interval | | 2sec | |
| Speed | | 4m/s | |
| Strip distance | | 100m | |

### 6.2.2 Local Field Trial at Connaught Water

A number of test flights were carried out in the United Kingdom (UK), in order to test the set-up of the camera and the overlap calculation detailed in section 6.1.2. Regulations in place in the UK for recreational flights of UAVs, as defined by the Civil Aviation Authority (CAA), impose severe restrictions on the feasibility of aerial mapping. According to these regulations, the pilot is to keep the UAV within line of sight at all times during a flight. The flight location must not be in proximity to any aircraft, airport or airfield and the flight height must stay below an altitude of 120 metres in order to avoid interference with manned aircrafts. Furthermore, having a camera attached, the UAV must be at least at a 50 metre distance from people or properties at all times. Crowds as well as built up areas must not be overflown (CAA, 2015).

The requirement to keep the UAV in sight while ideally testing the set-up over a forest terrain is challenging. Connaught Water in Epping Forest, situated between Greater London and Essex, has been identified as a suitable location for carrying out test-flights. The forest is close to London for feasibility yet away from airfields, built-up areas and traffic. Connaught Water's surrounding area offers extended visibility due to the flat surface of the lake as well as the car park situated in its close proximity. The area's suitability for testing was confirmed by carrying out a viewshed analysis.




***(a)*** *Take off location (Google Streetview, 2016)* ***(b)*** *Elevation relative to take off location*

***(c)*** *Viewshed from car park* ***(d)*** *Flight paths*

***Figure 6.12*** *Viewshed analysis*

A viewshed is defined as the visible area from a specified point of reference. A viewshed analysis takes into consideration the elevation of the area surrounding the point of reference in order to determine the visibility thereof.

To carry out a viewshed analysis of the UAV take off location near Connaught Water, a 1 metre resolution DSM, processed from LiDAR missions and provided by the Environment Agency (2014), was downloaded and loaded into QGIS. The UAV location was set to a clearing in between a car park and an area of dense tree population, shown in figure 6.12a. Next, the tree height in relation to the UAV location was determined by subtracting the height of the DSM raster cell of the UAV staring point from all other raster cells. The resulting model, shown in figure 6.12b, reveals that the height of tree canopy varies roughly between 5 and 15 metres in the forest area between UAV location and the lake. Knowing the canopy height, a viewshed analysis was carried out to identify the area visible to a UAV pilot from the car park next to the take off location. For this, a QGIS plug-in, developed by Cuckovic (2016), has been utilised with the elevation model calculated in the previous step and an observer height of 1.7m. Varying flying altitudes above the canopy were tested while taking into consideration that lower altitudes are beneficial for visibility. A flight altitude of 60 metres about ground gave satisfactory results in terms of visibility, shown in figure 6.12c.

Before being able to fit the flight path into the viewshed, the distance between strips was calculated using the algorithm detailed in section 6.1.2. The script to calculate flight parameters was run with to generate 60%/20% as well as 80%/30% endlap/sidelap combinations. The image interval was set to 5 seconds due to the shutter speed of the camera. The altitude for the algorithm was set to 50 metres given the average canopy height of 10 metres.

***Table 6.6*** *Flight parameters – Connaught Water*

| | 60/20 overlap | 80/30 overlap |
|---|---|---|
| Camera model | Canon PowerShot SX260 HS | |
| Focal length | 4.5 | |
| Sensor width | 6.17 | |
| Sensor height | 4.55 | |
| Altitude | 60m above ground (50m above canopy) | |
| Image interval | 5 seconds | |
| Speed | 4 m/s | 2 m/s |
| Strip distance | 54.8m | 48m |

The resulting values for speed and strip distance are shown in table 6.6. Knowing the strip distance, two flight pattern set-ups were overlaid in the area visible from the car park mainly covering forest area, including parts of the lake and footpath around it. The total strip length was 150 metres and the total distance between the two outermost strips was 144 metres and 164.4 metres respective to the overlap set-up.

### 6.2.3 Second field trial in the Republic of the Congo

The objective for the second field trial, carried out during the final visit to the RoC, was to generate maps to be used for map understanding experiments with the local population, detailed in chapter 7 as well as to acquire images with different cameras (see section 6.1.1), image overlaps (see section 6.1.2) and georeferencing methods (see section 6.1.3) to evaluate their suitability for map generation in given context, which directly contributes to answering Research Question 1: *How can appropriate base maps be created?* (see section 2.5).

As previously, the chosen field sites were the villages Sembola and Matoto, due to logistical reasons and the inhabitants, willingness to participate in research experiments. Table 6.7 presents an overview of the flight configurations chosen for the final field visit. Three experimental flights were carried out in Sembola, using the Canon camera and testing different strip distances. The experimentation phase was stopped abruptly when the UAV got temporarily confiscated by local authorities due to complications with obtaining official permission, further described in section 8.1.3. When the UAV was returned, a final set of flights was carried out in each village using the GoPro and a set-up that ensures a high overlap to guarantee for successful orthophoto generation that can be used for the map reading experiments described in sections 7.2 and 7.3.

***Table 6.7*** *Field trial 2 – flight parameters*

| Camera model | Canon PowerShot SX260 HS | | | GoPro Hero4 Silver | |
|---|---|---|---|---|---|
| Village | Sembola | | | Sembola | Matoto |
| Flights | 2 | 2 | 1 | 4 | 3 |
| Altitude | 60m | 60m | 60m | 60m | 60m |
| Image interval | 5sec | 5sec | 5sec | 1sec | 1sec |
| Speed | 3m/s | 3m/s | 3m/s | 3m/s | 3m/s |
| Strip distance | 120m | 80m | 50m | 100m | 100m |

## 6.3 Results

This section presents the intermediate and final results of the orthophoto generation process, using the data sets of Connaught Water (see section 6.2.2), Matoto and Sembola (see section 6.2.3). The structure mirrors the categories introduced in section 6.1 (see figure 6.1), presenting various comparative tests in regards to cameras, flight patterns, georeferencing and image processing methods. Finally, the proposed solution informed by these results will be outlined.

### 6.3.1 UAV and Camera

Various flights were carried out with both cameras, the Canon PowerShot SX260 HS as well as the GoPro Hero4 Silver. Each camera has several advantages and disadvantages for the application in photogrammetry (see section 6.1.1). This section compares the differences in weight and its effect on the resulting flight time, as well as the photo trigger software and shutter speed. Geotagging capabilities and lens distortion will be discussed in sections 6.3.3 Georeferencing and 6.3.4 Image Processing respectively.

One of the crucial limiting factors of multi-rotor UAVs, such as the Phantom 2, is the limited flight time due to its high power consumption (see section 3.1.1). DJI (2017c) report a flight time of 25 minutes per battery, which has presumably been achieved under ideal testing conditions and without any attachments to the aircraft.

The Phantom 2 aircraft has an inbuilt security feature to return to the starting position at maximum speed in case the remaining battery charge level drops under a critical threshold. This critical point is detectable in the flight through the sudden speed increase as well as by plotting the geotagged photographs through the increased gap in between the photographs. With 231g, the Canon PowerShot nearly triples the weight of the 83g of the GoPro action camera.

***Table 6.8*** *Flight time per battery*

| Camera | Flight | Flight time | Average flight time |
|---|---|---|---|
| Canon | 1 | 14:49 | 15:33 |
| | 2 | 15:58 | |
| | 3 | 15:53 | |
| GoPro | 1 | 15:10 | 14:57 |
| | 2 | 14:30 | |
| | 3 | 15:10 | |

In order to test whether the camera weight has an influence on the flight time, three flights with each camera set-up were examined. All were carried out in Sembola at a speed of three metres per second. Table 6.8 shows the elapsed time between take off and the critical point of return for each of the flights.

The results show no significant differences between the endurance of any of the six flights. The difference between the average flight time per camera is 36 seconds in favour of the heavier Canon PowerShot camera. The small degree of fluctuations is most likely influenced by the initial charge level and general performance of the various used batteries as well as external factors such a winds.

As discussed in the next section 6.3.2, the time interval between single photo shots is important given the requirement of high endlap to guarantee for successful image alignment. The GoPro camera's continuous shot function comes ready provided and allows for photographs being taken at a minimum of 0.5 seconds interval (see figure 6.2). The Canon camera's 'Intervalometer' function was provided by loading a script using the custom firmware CHDK. The script allows to freely set the desired interval in seconds. Tests revealed that the de facto minimum time interval in between shots lies between 4 and 5 seconds.

### 6.3.2 Mission Planning

In the literature, the common recommendation for endlap/sidelap combination between photos for orthophoto generation lies between 60/20% and 80/30%, see 3.1.1. Four flights were carried out in the test site Connaught Water, to test the validity of the flight parameter calculation, described in section 6.1.2, and to examine how the feasibility and quality of reconstruction is influenced by the amount of image overlay. The aim is to identify a configuration that creates enough redundancy to successfully align the images while keeping the overlap at a minimum to save battery power and processing resources. Less sidelap covers a larger extent during a single flight and the reduction of overlap generates less photographs, optimising time requirements during the stage of image processing. Using the proprietary software Agisoft PhotoScan, orthophotos could be created from the flights with 80/30% overlap. Executing the first step of the SfM pipeline – Image Alignment – revealed that only Flight 1 and Flight 2 with 80/30% endlap/sidelap combination could be aligned.

Figure 6.13 shows nine photos taken during Flight 2 with 80/30 percent overlap. The set of photos was manually aligned using photo editing software. The photo in the centre was overlaid with a raster, indicating the 80/30 overlap marks. The 80% endlap mark was met well, slightly exceeding the calculated overlap, which is likely due to the elevation having been set to 10 metres above ground height and the rounding of the calculated speed to 2m/s executed speed. The sidelap per strip was also exceeded throughout but, remarkably, the aircraft did not always move in a optimal forward facing direction, resulting strips of rotated images. An overview of all the aligned photographs overlaid on the sparse point cloud is shown on the lower right corner of figure 6.13.

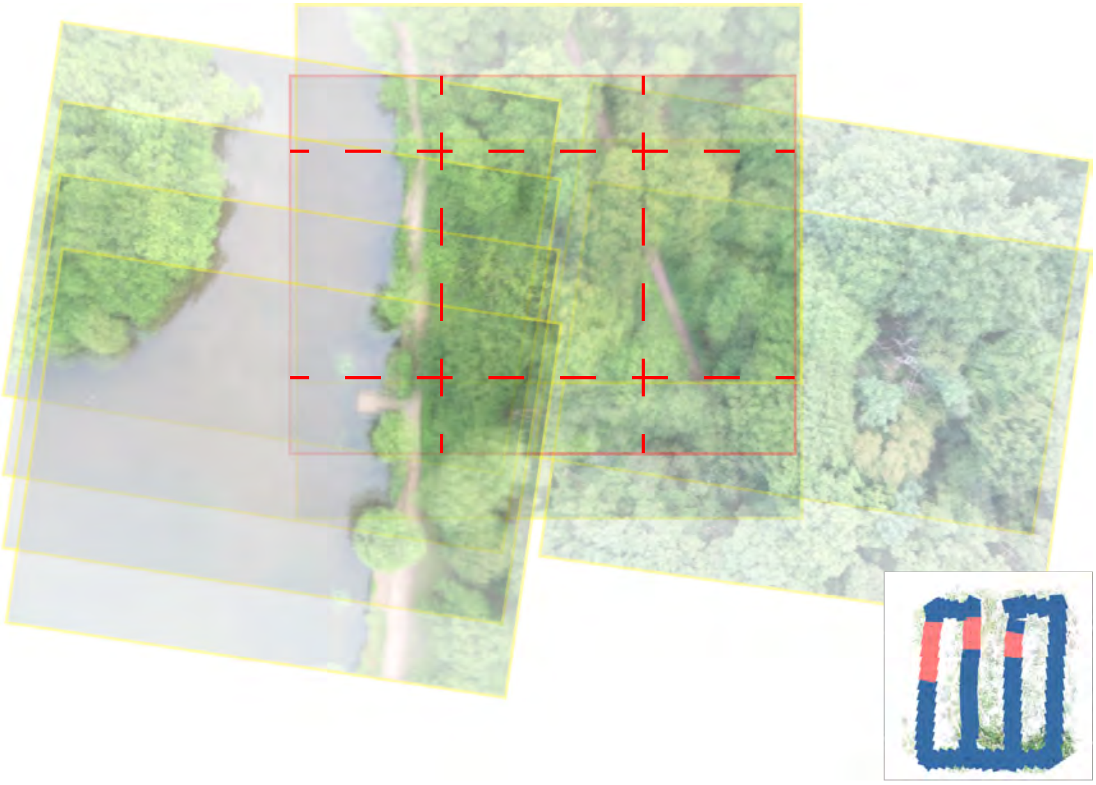


***Figure 6.13*** *80/30% overlap excerpt*

Figure 6.14 shows a selection of nine photos taken during Flight 4 with 60/20 percent theoretical overlap. Like above, the photos were manually aligned with the one in the centre showing the 60% and 20% marks. Neither PhotoScan nor OpenDroneMap was able to align the photographs although all overlaps were exceeded and the photos are better aligned than in 6.13. Both flights were carried out above the same landscape and thus show the same amount of distinct features and quality of the photographs is comparable. This indicates a high importance of the endlap for successful automated image alignment.

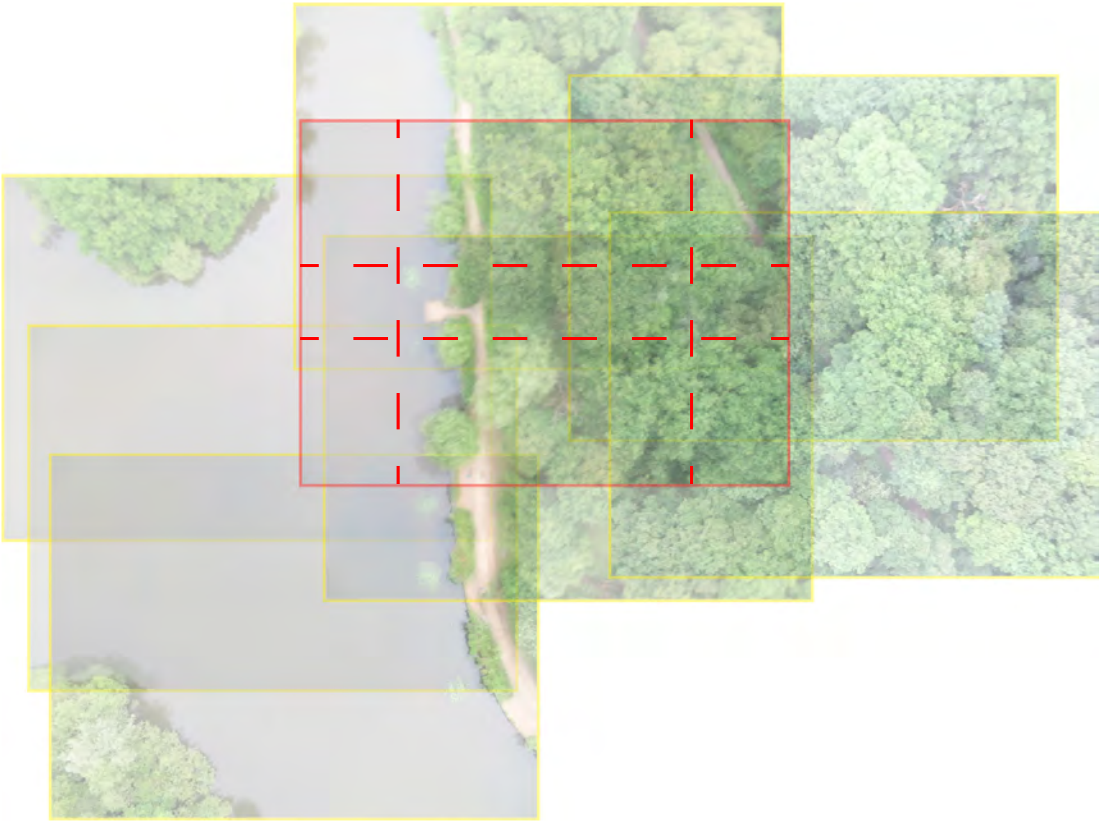
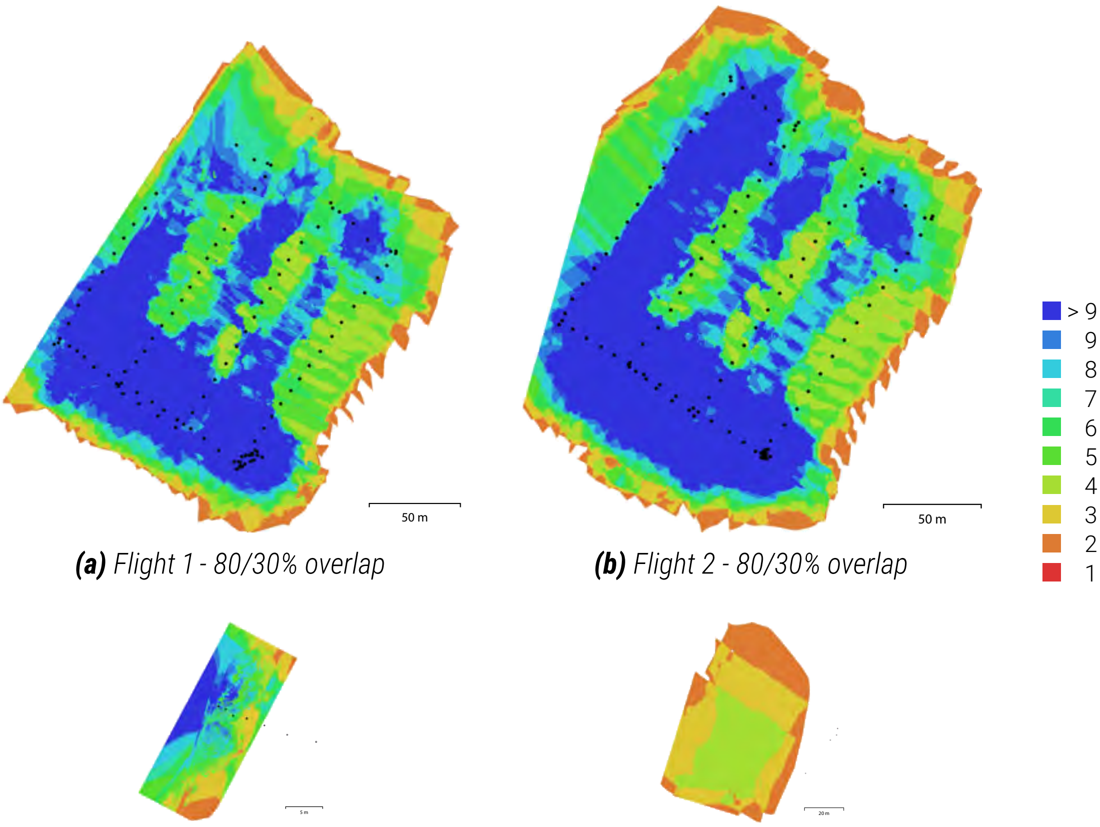


***Figure 6.14*** *60/20% overlap excerpt*

***Table 6.9*** *Results Connaught Water*

| | Overlap | Effective overlap | Photos / Aligned Photos | Re-projection Error (RMS) |
|---|---|---|---|---|
| Flight 1 | 80/30% | 2.64677 | 116 / 108 | 2.24252 pix |
| Flight 2 | 80/30% | 2.79054 | 112 / 112 | 2.26062 pix |
| Flight 3 | 60/20% | – | 14 / 70 | – |
| Flight 4 | 60/20% | – | 4 / 72 | – |

The effective overlap, referred to in table 6.9, refers to the mean number of photos, in which each point in the sparse point cloud is visible in. Figure 6.15 shows image overlap maps in relation the aligned camera positions after the scene reconstruction, produced using the PhotoScan application. Figures 6.15a and 6.15b show areas of high overlap in between the strips, in many areas exceeding 9 overlapping images. The areas underneath the camera positions show an average of 4-6 overlapping images, with higher number for where the UAV has passed by twice due to the return route. Figures 6.15c and 6.15d show the parts the software aligned, which, according to visual inspection, do not seem to be correctly aligned.




***(a)** Flight 1 - 80/30% overlap*

***(b)** Flight 2 - 80/30% overlap*

***(c)** Flight 3 - 60/20% overlap*

***(d)** Flight 4 - 60/20% overlap*

***Figure 6.15*** *Connaught Water – image overlaps*

In the Republic of the Congo in the village of Sembola (see figure 5.2), five flights were carried out with varying strip distances and in perpendicular flight directions. Building on the results of the test flights at Connaught Water, which showed the importance of the endlap, the aim now was to test whether insufficient sidelap allows for image alignment. Furthermore, two flights were carried out over the same area on the following day at a different time of day, to test whether the image sets can be aligned despite varying light conditions.

According to the flight parameter calculations, at a speed of 3 metres per second and a flight altitude of 60 metres, an 80% endlap can be achieved. The 0% sidelap threshold lies at a strip distance of 82.27 metres. The first day at 8:30am, two flights were carried out consisting of four flight strips each at a distance of 120 metres from each other to explicitly undercut the required sidelap. On the following day, another three flights were carried out, two of which overlaid the previously captured areas with flight strips at perpendicular directions. Each flight pattern consisted of 6 flight strips at a 80 metres distance from each other, which was expected to result in approximately 0% sidelap. A third flight, south of the previously captured areas, was carried out at a 50 metres strip distance consisting of three strips. The results are shown in figure 6.16.

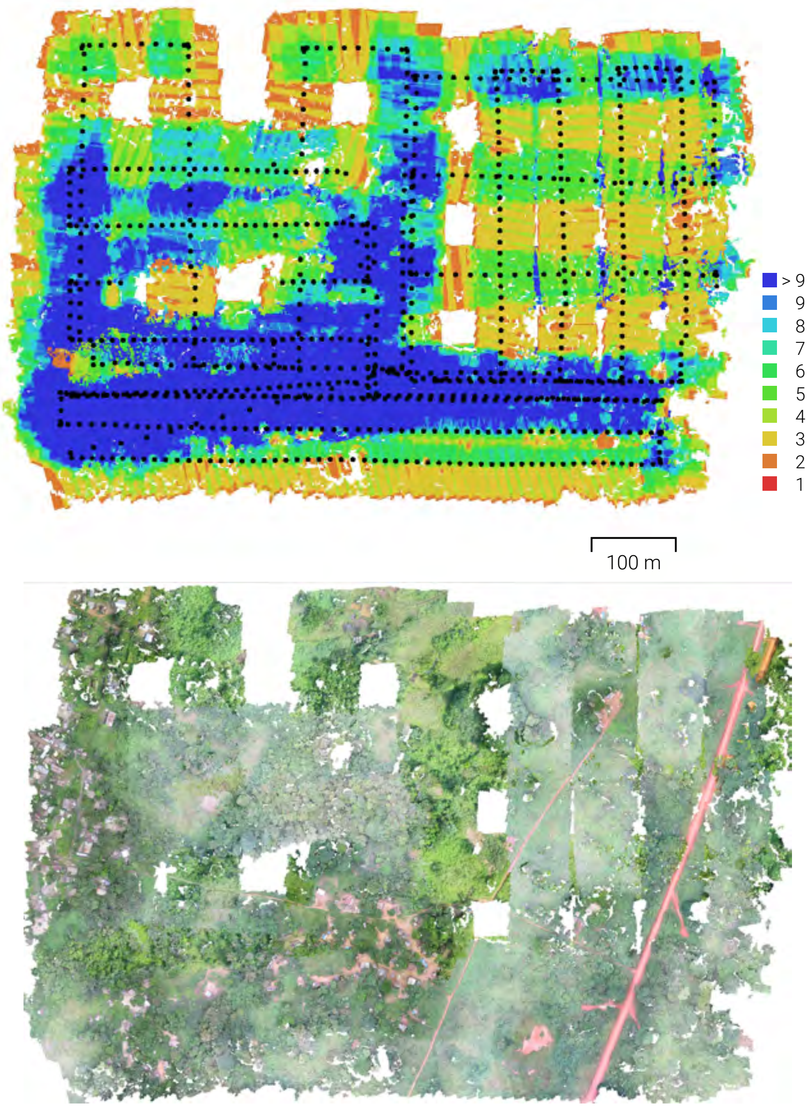
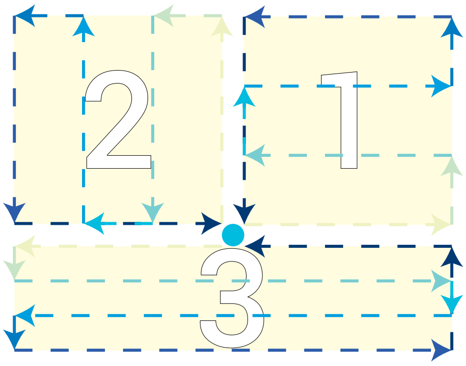


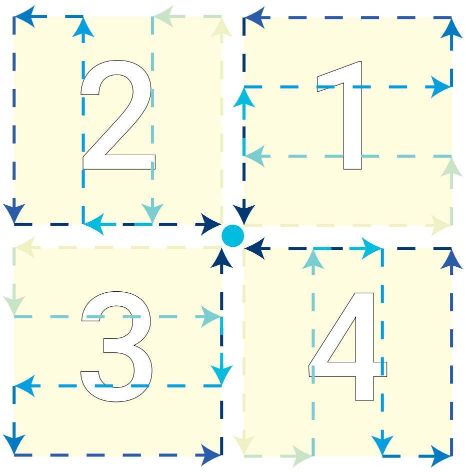

***Figure 6.16*** *Sembola – varying strip distances and light*

The results show that all images taken during the first day were successfully aligned on the basis of the endlap. The images taken at a flight strip distance of 80 metres could be merged where the sidelap was existent. To the north-east of the resulting images, four flight strips could be aligned based on the endlap but the 80 metres strip distance was not enough to merge the alignment of the separate flight strips. In both flights, one strip failed to align correctly. The flights taken on different days and times with varying lightning conditions could be merged into one point cloud and finally orthophoto.

In order to create orthophoto maps to be used for the map reading experiments discussed in chapter 7, three flights were carried out over the field site of Sembola Matoto (figure 6.17a) and Sembola (6.17b). The flight parameters were set to 60 metres with a strip distance of 90 metres and 2 seconds photo interval. According to the calculations, a 80/30 overlap could be achieved with a speed of 11 metres per second and a strip distance of 130 metres. In order to have enough overlap to generate valid maps, the approach was taken to take an abundant amount of photographs to guarantee for successful orthomap creation and additionally allow for the experimentation with varying levels of endlap by omitting certain photographs during the SfM reconstruction process.




***(a)*** *Matoto*




***(b)*** *Sembola*

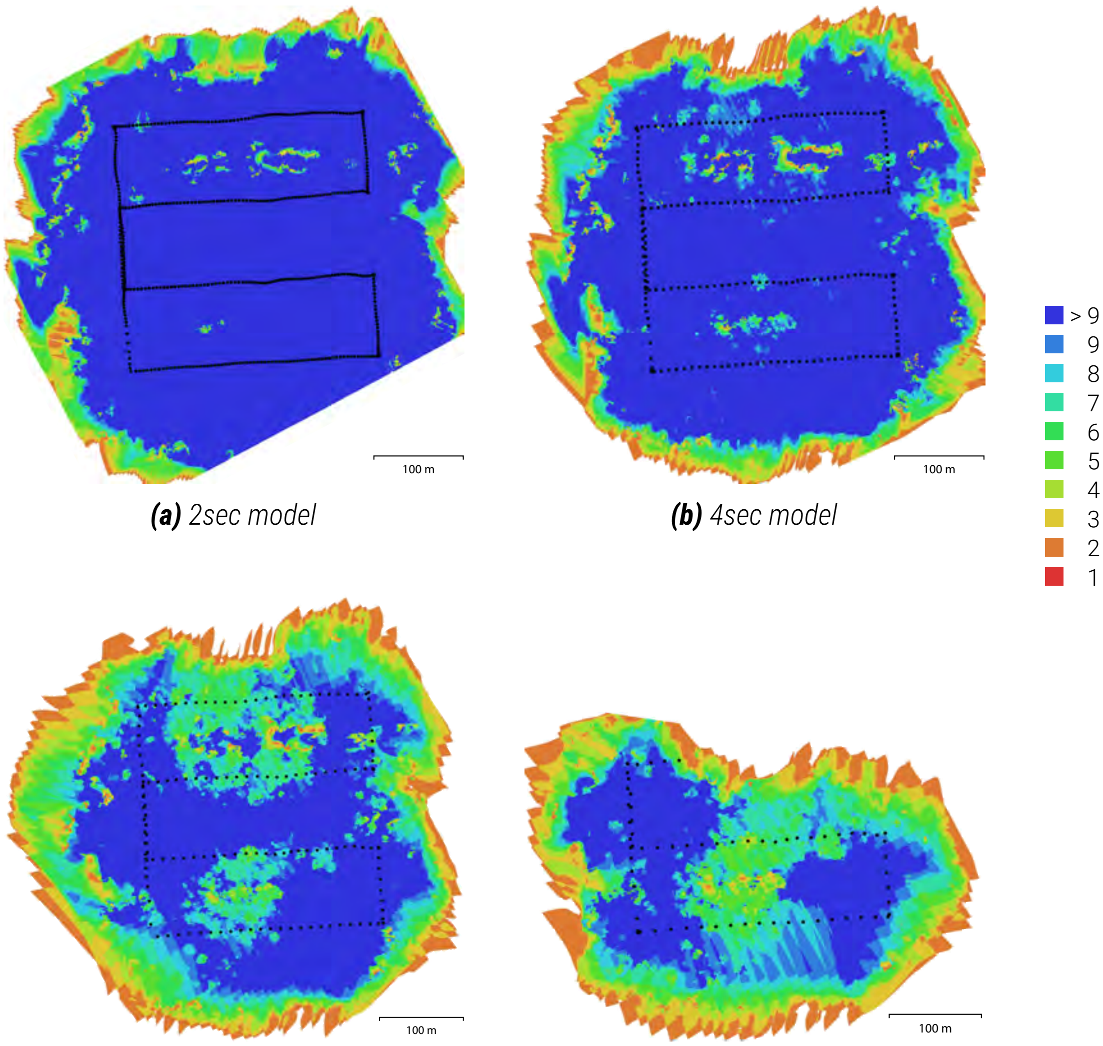
***Figure 6.17*** *Flight patterns*

Table 6.10 and figure 6.18 show the alignment results for flight number 1 in Matoto. In addition to the entire set of photos, taken at a 2 seconds interval, subsets of 4, 6 and 8 seconds intervals were aligned. The results show that the image sets with 95%, 90% and 85% endlap could be fully aligned, with the subset having aligned 71 out of 116 photographs. While the effective overlap is increasing with the amount of photographs, the Root Mean Square Error (RMSE)[3] of the computed re-projection error shows its lowest value (0.707231 pixels) at the 6 seconds subset. The re-projection error is generally low, showing only little variation.

[3]Measure for deviation between predicted and observed values

*Table 6.10* Results Matoto GoPro

| Interval (seconds) | Endlap | Effective overlap | Photos / Aligned Photos | Re-projection Error (RMS) |
|---|---|---|---|---|
| 2 | 95% | 4.04083 | 439 / 439 | 0.733994 pix |
| 4 | 90% | 3.00102 | 232 / 232 | 0.760892 pix |
| 6 | 85% | 2.58611 | 146 / 146 | 0.707231 pix |
| 8 | 80% | 2.61868 | 116 / 71 | 0.782758 pix |




**(a)** *2sec model*

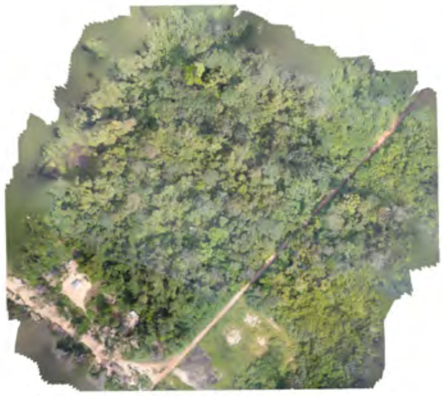
**(b)** *4sec model*

**(c)** *6sec model*

**(d)** *8sec model*

***Figure 6.18*** *Matoto – endlap variations*

Figures 6.18a and 6.18b show a high amount of overlap with most parts being visible in more than 9 photographs. Figure 6.18c shows areas between the strips visible in only 2-3 photographs but nonetheless showing full alignment. Figure 6.18d, representing the subset with 80% endlap has not been fully aligned with the missing part covering dense rainforest area.



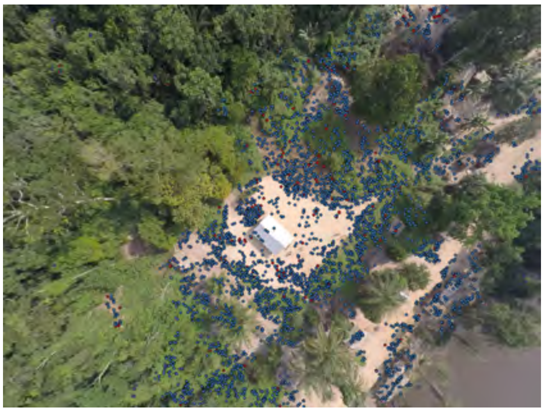
***(a)*** *Matoto - 2sec model*

***(b)*** *Matoto - 8sec model*

***Figure 6.20*** *Endlap of unaligned photos*

Figure 6.20, shows three of the unaligned photographs, manually aligned using a graphic editor. While the 80% endlap has been achieved, it is likely that the similarity and missing texture in the forest pixels contributed to the difficulties in finding robust keypoints (see section 3.1.2). Visualising the tie points of a an unaligned photograph depicting an area of dense forest canopy in figure 6.21a, reveals that only few tie points were identified compared to an aligned photograph showing diverse texture, see figure 6.21b. The red dots indicate identified tie points, while blue dots show matched tie points.

***(a)*** *Unaligned photo*



***(b)*** *Aligned photo*

***Figure 6.21*** *Tie points*

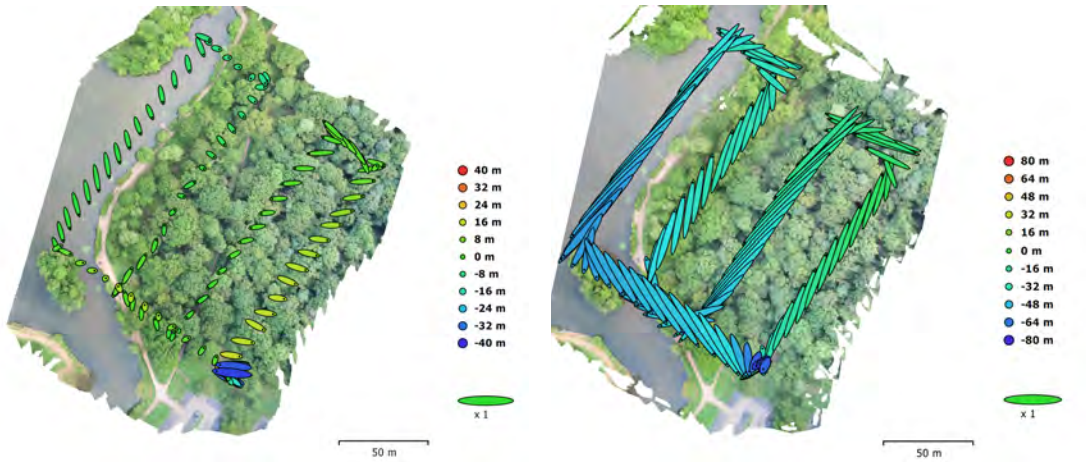
### 6.3.3 Georeferencing

This sections presents the results of georeferencing the orthophotos. Four methods were tested and compared: direct geo-referencing through GPS enabled camera, direct georeferencing through geotagged photos using Flytrex data logger, indirect georeferencing using GCPs, and a hybrid approach combining direct and indirect methods.

Table 6.11 shows the RMSE camera error estimates in X/Y direction reported by the PhotoScan application when using direct georeferencing methods (Canon or Flytrex) for the test flights carried out at Connaught Water. The results of the direct methods reveal that, when attempting to match the aligned point cloud with the given camera positions, the residual errors are higher using the Flytrex data logger than the cameras. This outcome is surprising, because, as explained in section 6.1.3, the data logger directly plugs in to the UAV's GPS module, reading the same values while the Canon camera's GPS receiver operates independently. Looking at the visualised results in figure 6.22 depicting camera locations along with error estimates for the highest and lowest reported values, reveals that the camera error for the Canon photos appear random while the Flytrex camera errors are higher in total value but strikingly systematic. Given that the photographs were geotagged with the aircraft's location at the time the photo was taken, the most likely explanation for the high systematic error is a time-offset in the synchronisation process.

***Table 6.11*** *Camera errors – Connaught Water*

| | Flight 1 | | Flight 2 | |
|---|---|---|---|---|
| | Camera Error | Marker | Camera Error | Marker |
| Canon | 12.4894 | 16.0154 | 8.00639 | 9.39995 |
| Flytrex | 28.7896 | 25.8072 | 29.764 | 36.2142 |




***(a)*** *Flight 2 - EXIF set-up* ***(b)*** *Flight 2 - Flytrex marker set-up*

***Figure 6.22*** *Relative camera errors*

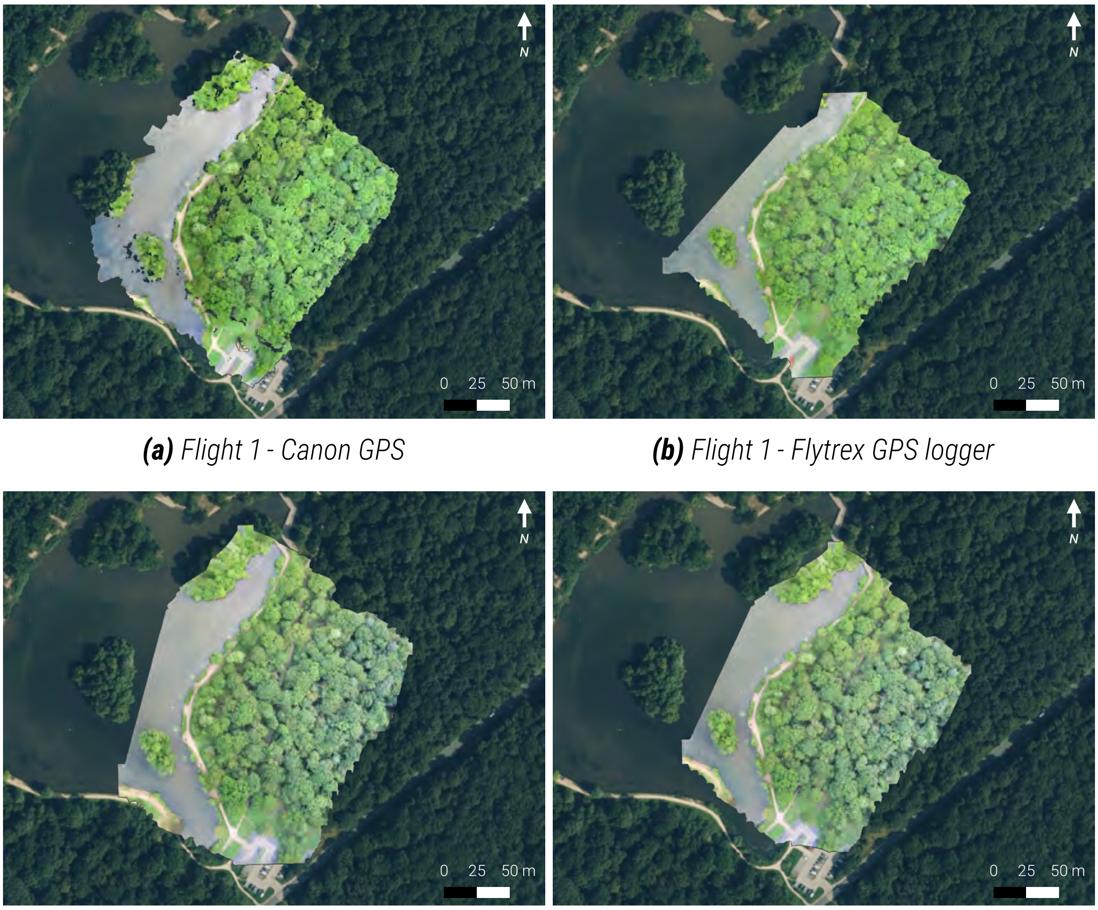
For the test in Connaught Water, the photos were geotagged, meaning that there is no need to accurately match camera's clock with the GPS log as the photographs hold precise GPS time values. This excludes the possibility of an incorrect camera time in this scenario. An issue that has been explored is the location ambiguity due to the time format precision. The Flytrex module logs time stamps accurate to one second. At a speed of 2 metres per second, the time-synchronised camera location might add a locational error of up to 2 metres to the given GPS inaccuracy. In order to investigate the dimension of this issue on the result, a Python script was written to automatically extract first and last possible location to match each taken photograph and save it as a new log file. This file was then synchronised using the Geosetter software. The resulting errors when processing both generated image sets for Flight 2 are shown in table 6.12. The difference in RMSE in XY direction is less than one meter and cannot be the critical factor to cause the observed time offset.

***Table 6.12*** *Camera errors first point / last point*

| | X error (m) | Y error (m) | XY error (m) |
|---|---|---|---|
| First location | 20.0195 | 22.0343 | 29.7706 |
| Last location | 19.4704 | 21.4666 | 28.9812 |

The previous section looked into error residuals when georeferencing the aligned images using given methods. In order to judge the absolute accuracy, the generated orthophotos were overlaid on a high quality orthophoto of 25cm resolution by EDINA Aerial Digimap

Service (2014). Figure 6.23 shows that both direct georeferencing methods show little overall accuracy, which is most visible in the area of the parking lot towards the southern edge of the photo. The rotation effect is clearly visible in the aerial maps that were geotagged with the Flytrex data logger (see figures 6.23b and 6.23d).

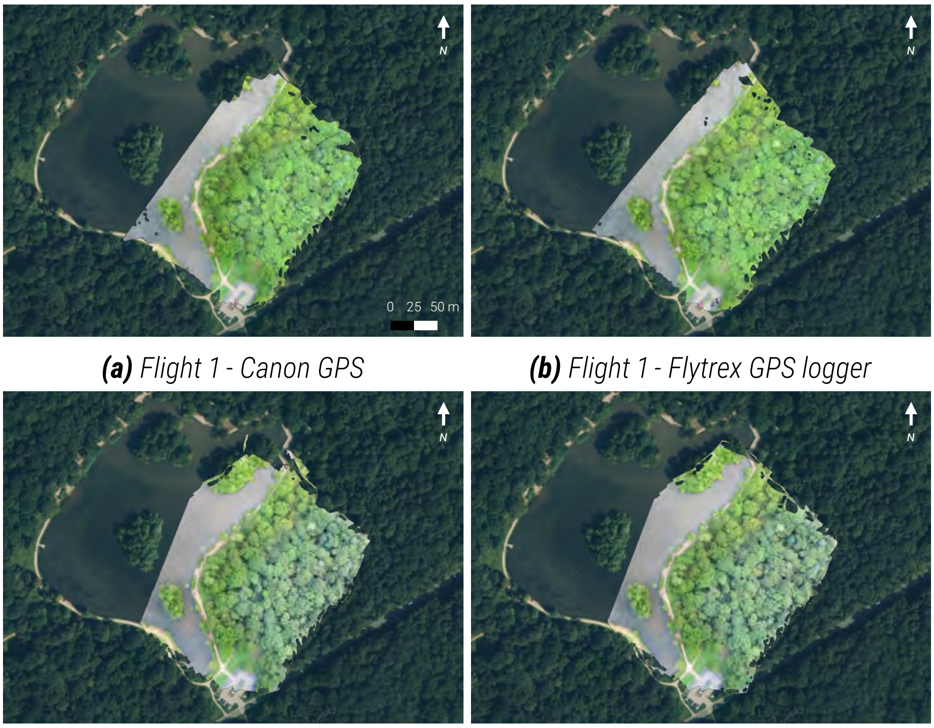



***(a)*** *Flight 1 - Canon GPS*
***(b)*** *Flight 1 - Flytrex GPS logger*
***(c)*** *Flight 2 - Canon GPS*
***(d)*** *Flight 2 - Flytrex GPS logger*

***Figure 6.23*** *Connaught Water – total reference*

To improve the results, a hybrid approach of inserting three absolute reference points into the photo alignment process was tested. No GCPs were taken at Connaught Water, however, as a proof of concept, the reference points were obtained by identifying fixed positions on the ground visible in both the downloaded orthophoto as well as the taken photographs (see figure 6.24). After retrieving the latitude/longitude values of three points marking the corner of the parking lot (1), the picknick table (2) as well as the corner of the footbridge (3) from the aerial orthophoto, they were inserted as 'markers' in the PhotoScan processing chain. As figure 6.25 shows, the resulting orthophotos are correctly aligned.


***Figure 6.24*** *Epping Forest – GCPs*




***(a)*** *Flight 1 - Canon GPS*

***(b)*** *Flight 1 - Flytrex GPS logger*

***(c)*** *Flight 2 - Canon GPS*

***(d)*** *Flight 2 - Flytrex GPS logger*

***Figure 6.25*** *Connaught Water – total reference hybrid*

In Matoto, four GCPs were taken, using a Garmin GPS 60 device. Two methods of georeferencing were tested and compared: using GCPs only, as well as a hybrid, approach with Flytrex geotagged photographs. The results of both methods were identical. In order to evaluate the absolute accuracy of the orthophoto in absence of a reference map, the paths travelled by the Treasure Hunt participants, described in section 7.2.3, as well as the derived network were overlaid as shown in figure 6.26.


***Figure 6.26*** *Matoto – manual georeferencing*

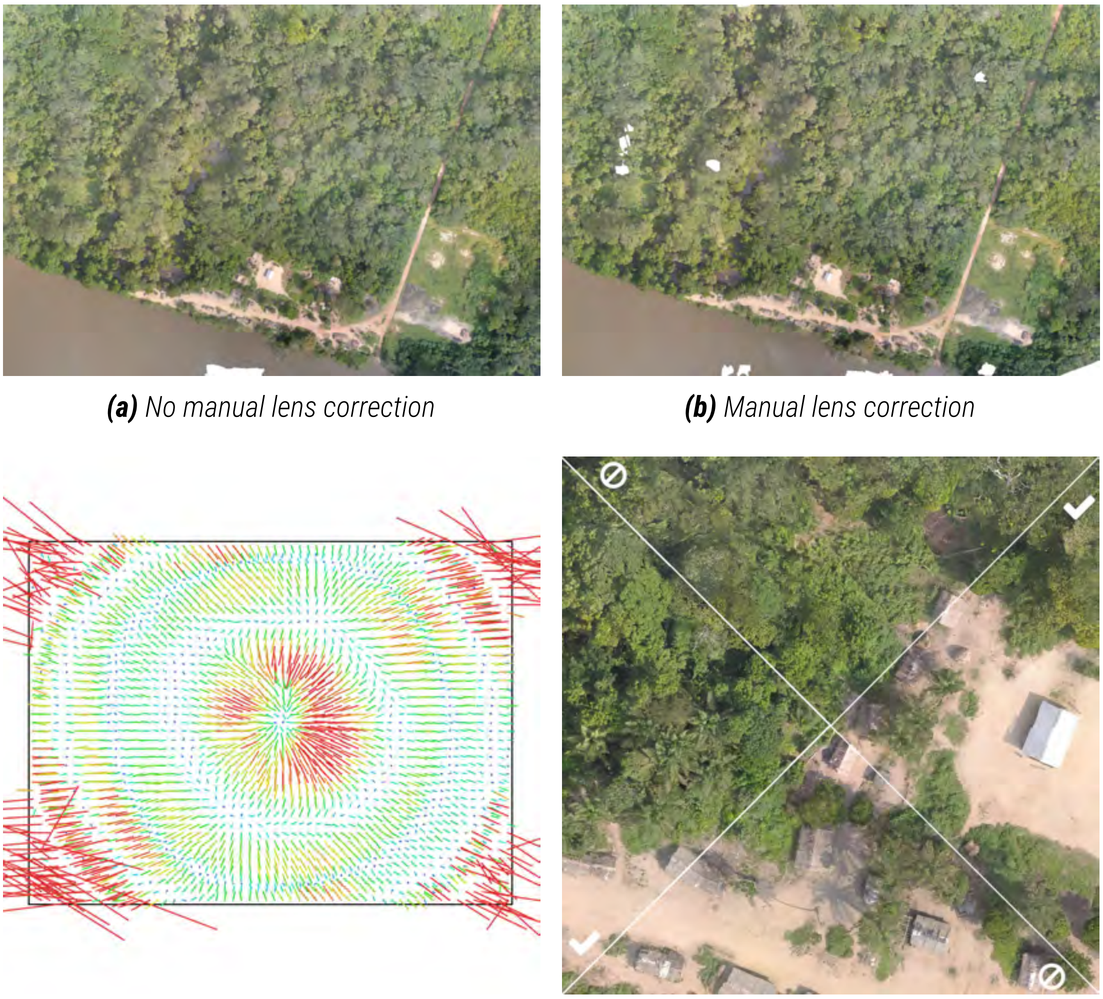
The results show a good overall fit, with the GPS track overlays following the paths, where visible, and circumventing obstacles such as huts and trees. In the west of the village, the network path runs through trees and seems to be slightly off. Given that the path data were recorded with the GPS receiver of a consumer grade Android tablet (see 7.2.1), it is uncertain whether the orthophoto, the network path or both are inaccurate.

### 6.3.4 Image Processing

This section discusses the results or manual removal of barrel distortion, the time requirements of orthophoto processing as well as the attempts of processing the capture image sets with the open-source software OpenDroneMap.

*Image Distortion*
A set of images taken in Matoto with a GoPro camera was processed in PhotoScan, with and without manual lens correction using the application PTLens (see 6.1.4). The results are shown in figure 6.27. Figure 6.27a was processed using raw photographs with barrel effect while figure 6.27b was processed with corrected photographs. Both orthophotos show no evidence of barrel distortion, while the latter one has holes in areas between the flight strips where the photos are supposed to be overlapping, due to the cropped edges. Looking at the image residuals reported by the application (see figure 6.27c), reveals that

PhotoScan detected the barrel distortion and corrected for the pixel misplacement in the image matching algorithm. Comparing both results at a higher zoom level shows that both images are perfectly aligned and the shapes of roof and tree canopy are geometrically correct in the orthophoto without prior lens correction (⊘) as well as with lens correction (✔).



***(a)*** *No manual lens correction*

***(b)*** *Manual lens correction*

***(c)*** *Image residuals*

***(d)*** *Result comparison*

***Figure 6.27*** *Effect of barrel distortion on orthophoto*

**Processing Time**

When working in the field it is crucial to factor in a realistic processing time in order to efficiently organise the field visit. For this project, all image processing using PhotoScan was carried out on a Dell XPS 15 laptop, equipped with 16GB RAM and an i7 processor with four cores and a clock speed of 2.30GHz. Processing time might vary depending on the equipment and running background processes. During processing for this project no other applications were running on the same machine.

Agisoft PhotoScan enables the user to define various settings during the SfM process and often quality parameters can be set either 'low', 'medium' or 'high'. While the exact meaning of these is not further specified, initial trials showed that choosing higher quality parameters may significantly increase processing time. Due to the importance of successful photo alignment (see section 6.3.2), the quality parameter was set to 'high' and decreased to 'medium' for the resource consuming stage of dense point cloud generation. To even further reduce the time requirements of this stage, trials were processed, in which the amount of photos was decreased by half for scene reconstruction. Figure 6.28 shows the processing requirements of the stages 'photo alignment', 'dense point cloud generation' and 'mesh generation' in relation to the number of photographs.

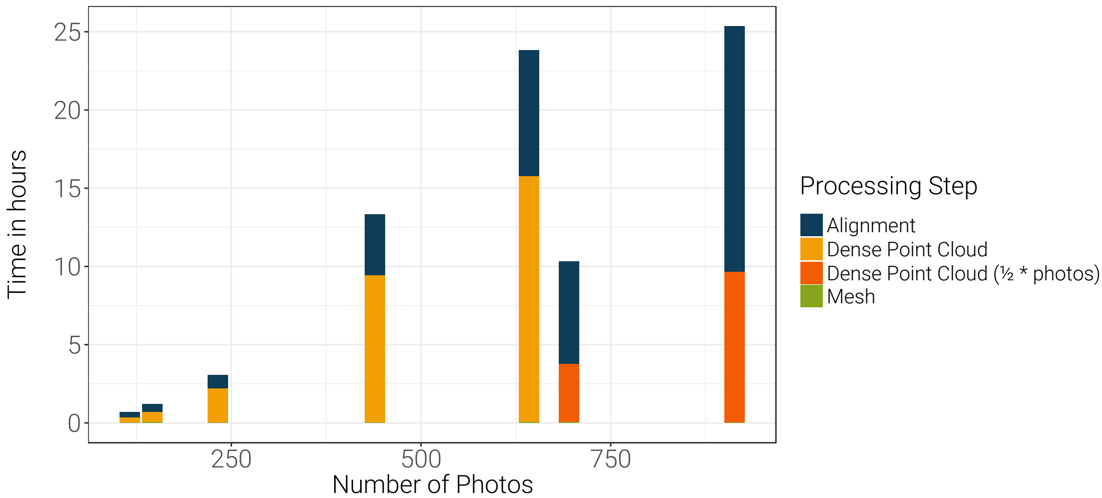



***Figure 6.28*** *Time requirements for scene reconstruction*

Figure 6.28 shows that processing time increases considerably with the number of photographs. A dataset consisting of 642 photographs could be processed within 23 hours 50 minutes. Halving the amount of photographs during the dense point cloud reconstruction showed significant decrease in total time requirements. The dataset of Matoto, consisting of 695 photographs, could be reconstructed within 10 hours 20 minutes. Sembola, consisting of 913 photographs required 25 hours 22 minutes for scene reconstruction.

#### OpenDroneMap

As a free and open alternative to Agisoft PhotoScan, the image sets were processed with OpenDroneMap (see section 6.1.4). Due to high memory consumption and repeated software failures, only the images taken at Connaught Water (with 80/30% overlap) and one flight taken in Matoto produced orthophoto results. Figure 6.29 shows an orthophoto generated from the 116 geotagged photographs taken during flight 1 at Connaught Water (see table 6.9). In order to judge absolute geographic reference, previously used GCPs (parking lot corner, picknick table and footbridge) (see section 6.3.3) were used as checkpoints and overlaid at their actual coordinates.

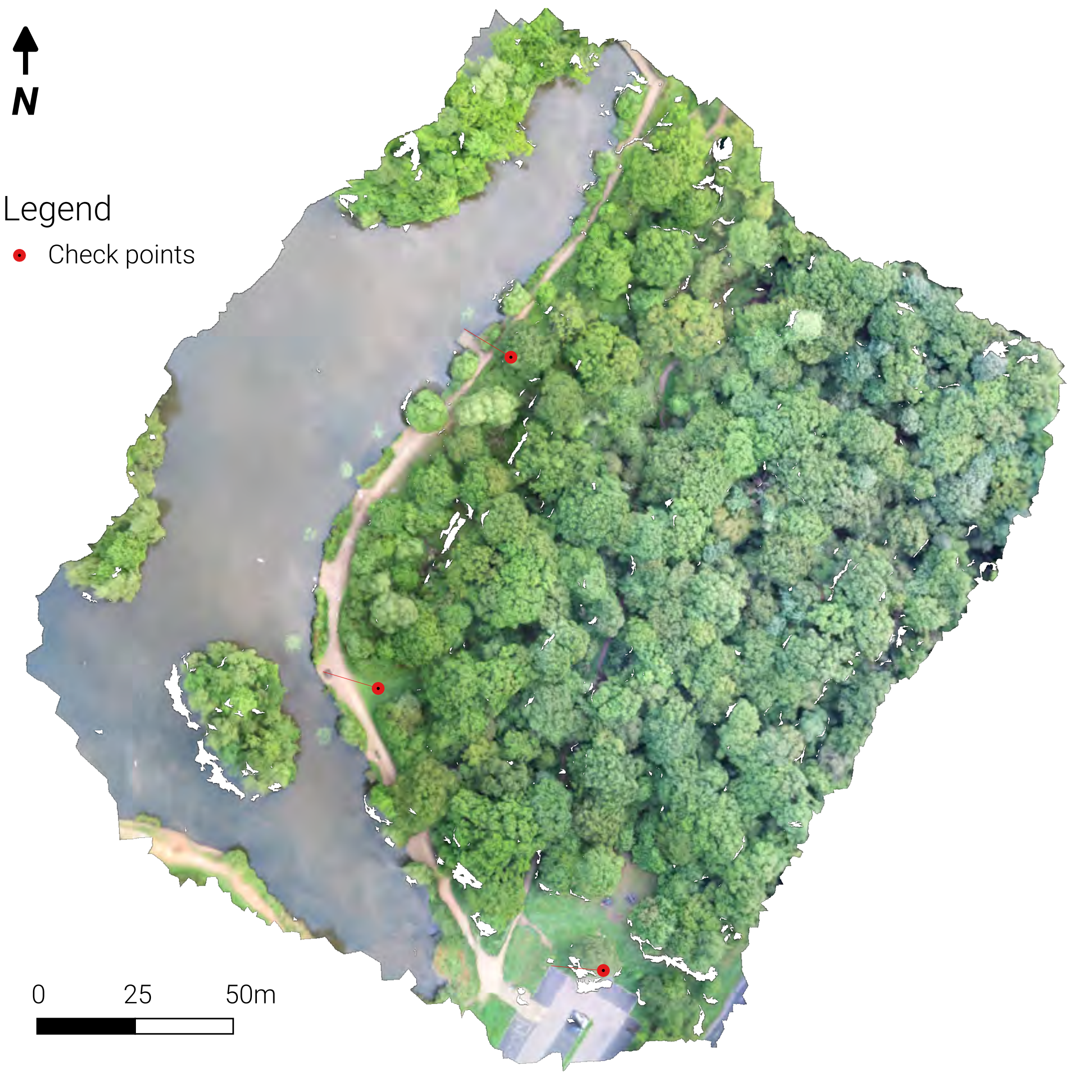



***Figure 6.29*** *Connaught Water*

Figure 6.30 shows an orthophoto generated from a subset of 187 photographs taken during a single flight in Matoto with a GoPro camera. The selection was made by decreasing the endlap to 80% in order to reduce memory consumption. The photographs were corrected for barrel distortion as described in section 6.1.4 and geotagged using the Flytrex log information as described in section 6.1.3. In order to judge absolute geographic reference, the recorded paths taken by participants during the Treasure Hunt experiment (see section 7.2) was overlaid.

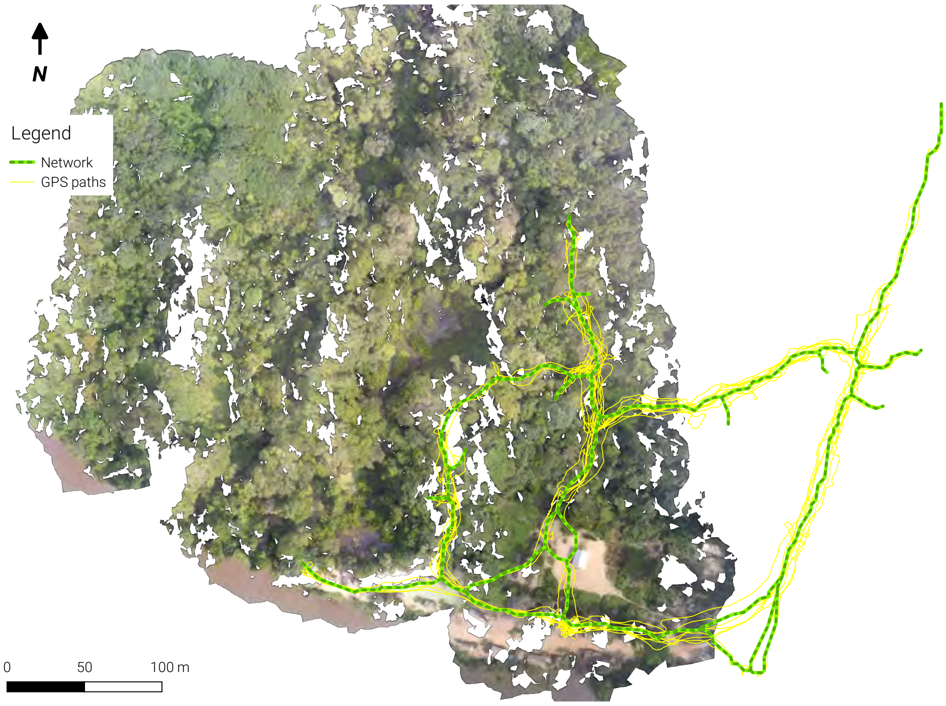



***Figure 6.30*** *Matoto – flight 1*

### 6.3.5 Final Orthophoto Maps

Taking the results of previous sections into consideration, two orthophotos were generated by flying a 90% endlap, 30% sidelap configuration with the GoPro Silver Hero4 action camera. In each village, four GCPs were taken using the Garmin GPS 60 device and manually inserted as markers during the image alignment phase in Agisoft PhotoScan. To reduce processing requirements, the endlap was decreased to 80% during the stage of scene reconstruction. Table 6.13 shows the amount of photos taken per site, the time required for processing as well as the final size and resolution of the orthophotos.

Figures 6.31 and 6.32 show the resulting orthophotos of the villages Matoto and Sembola and figures 6.33 and 6.34 illustrate the level of detail and the visual quality of the results in full resolution for both forest and village areas. The final digital orthophotos can be found in Appendix A.5.

***Table 6.13*** *Final results*

| | Images | Time | Size | Resolution |
|---|---|---|---|---|
| Matoto | 695 | 10 h 20 min | ~600 m x 450 m | 10 cm |
| Sembola | 913 | 25 h 22 min | ~600 m x 600 m | 10 cm |


***Figure 6.31*** *Matoto*

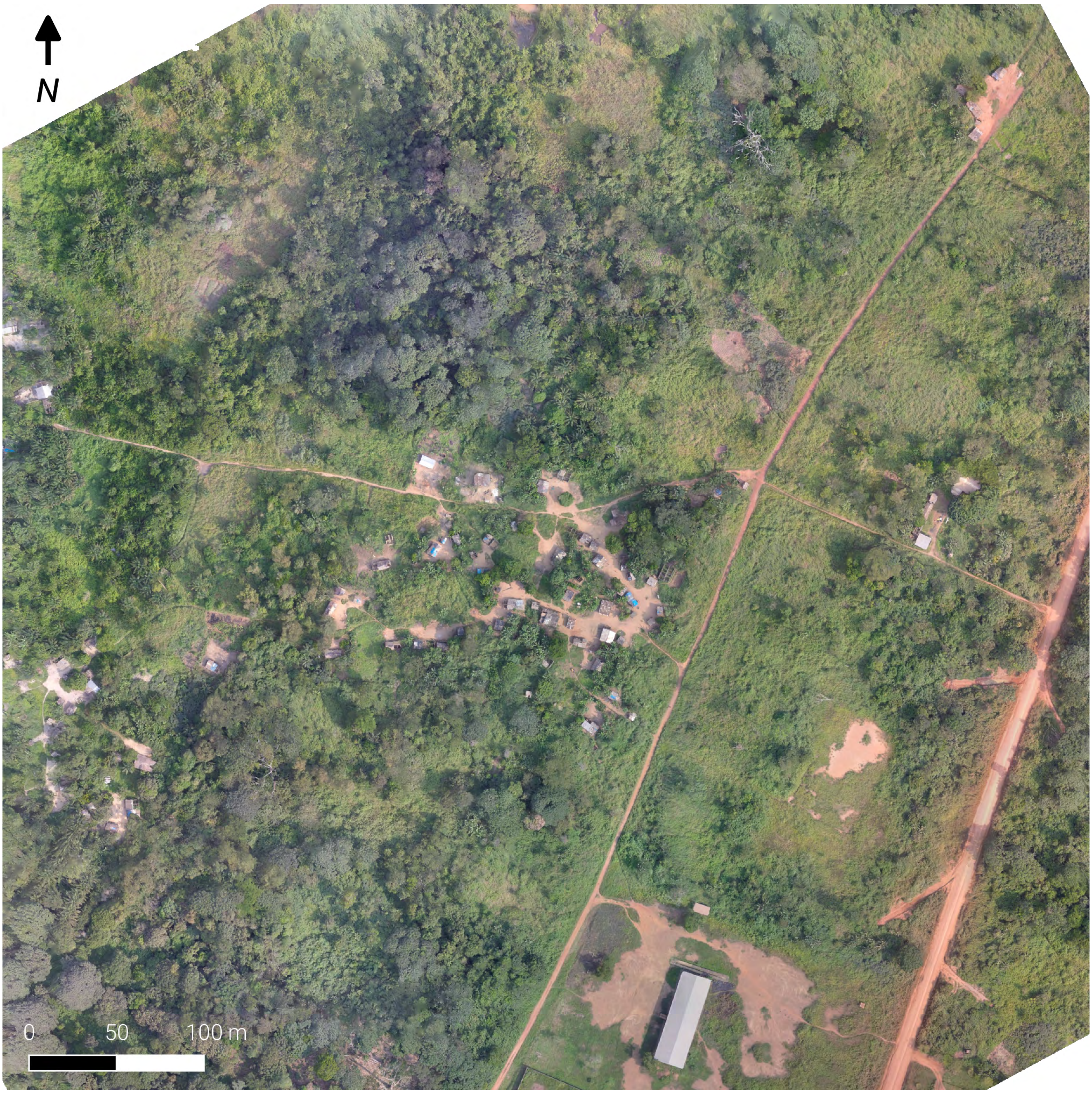



***Figure 6.32*** *Sembola*

***Figure 6.33*** *Matoto – full resolution*

***Figure 6.34*** *Sembola – full resolution*

## 6.4 Discussion

Several limitations need to be taken into consideration when generating orthophoto maps derived from UAV-borne image acquisition in remote rainforest areas. This section discusses the results with named limitations in mind, resulting in a suggested image acquisition processing pipeline.

Both tested cameras have proven suitable for generating orthophoto maps. The flight speed of the heavier Canon camera model did not have a negative impact on the flight duration. On the other hand, the geotagging capabilities were not found to be crucial due to their low accuracy. This feature would only be advantageous if there was no access to GCPs, which will be further discussed later in this section. Factors that had a bigger impact on the results were the slow photo trigger speed of the Canon model, resulting in 4-5 seconds intervals in between single shots resulting in a smaller endlap. Furthermore, the custom CHDK was not particularly user friendly and caused the camera to shut down after a few minutes when the GPS function was switched on via the custom firmware. This was eventually resolved by booting back into the default firmware and switching on the GPS listener before switching back to Intervalometer mode. There was no obvious connection between these functions and therefore it took many trial and error attempts to identify and solve the problem. The GoPro's barrel distortion did not have negative impacts on image alignment or other stages of the SfM process if enough overlap was provided and if the maximum trigger speed of the action camera was as little as 0.5 seconds.

Various tests at the site of Connaught Water as well as Matoto have shown that a high endlap has a bigger impact on the success of photo alignment than a high sidelap. Image alignment is specifically important as it is the step to estimate camera positions, which are essential for scene reconstruction. Especially in areas with little distinct texture, such as areas with dense canopy cover, a higher overlap was required due to less tie points detected by the image matching algorithms.

In the literature, it is commonly recommended to be generous with image overlap (Greenwood, 2015). Increasing endlap and sidelap, to guarantee for successful scene reconstruction through SfM, comes at the cost of increased processing time, especially given the relatively low performance of current laptops. Resource heavy processing, as required for SfM scene reconstruction is typically carried out using powerful servers accessible through the cloud. In an offline scenario, however, that is not an option and the hardware specifications recommended by Agisoft, detailed in section 6.1.4, could not be met by any of the available consumer oriented laptops. A focus of this project was to ensure enough overlap to generate suitable results, but decrease image redundancy to an amount where processing requirements are manageable for in-situ map generation. The processing threshold for this project was set to a maximum duration of 24 hours. Another limiting factor, especially when using multi-rotor aircrafts, is flight time due to high power consumption, which severely restricts the size of the area to be captured. The recommended approach, resulting from the results shown, is to generate a high endlap by decreasing the interval in between shots and reduce sidelap if required.

In the developed part of the world, countries commonly have national positioning infrastructure in place to derive accurate locations in order to georeference new mapping products. In the UK, the national mapping agency, Ordnance Survey, maintains a network of continuously operating reference stations (CORS) to cover the entire country, with no point being further than 75km away from the nearest reference station (Ordnance Survey, 2017). When new maps are being created, points of reference at a sub-metre accuracy can be obtained for absolute reference. In aerial mapping, a number of precise Ground Control Points (GCPs), spread evenly across the area to be mapped, are current best practice to obtain absolute reference. In the rainforest of the Republic of the Congo, there is no surveying network and obtaining GCPs has to be based on consumer grade GPS receivers with horizontal inaccuracies usually in the range of several metres. In addition, the ground is often not visible when mapping dense rainforest areas, which severely limits the possibility to obtain good coverage of an area.

Given these limitations, two methods of direct georeferencing have been investigated in order to evaluate their suitability for creating accurate maps with no absolute reference points. The Canon camera's GPS receiver has shown inaccuracies of several metres, resulting in insufficient overall accuracy. Using the UAV's location readings directly, had higher precision but even less overall accuracy due to unpredictable time offset. In an attempt to find the source of the error, the possibility of time offset between the Canon camera and the data logger was excluded due to using the highly accurate GPS time. However, the data logger as well as image time stamp were logged accurate to one second, which results in an added inaccuracy of 2 metres, if flown at a speed of 2m/s. Tests have shown that this could not have caused an offset of given dimension and neither could the problem be traced back to an error in the decoder, written by Racicot et al. (2014), as it was compared to the results obtained through the Flytrex data upload. Due to excluding the described potential error sources, it is likely that the offset occurred during the geotagging process. Given that the error could not be removed, the data logger option is considered as not suitable, especially when using cameras that do not have access to accurate GPS timestamps, such as the GoPro. The highest location accuracies were achieved by adding GCPs as fixed marker locations after the image alignment stage. The GCP were captured with a handheld Garmin GPS 60 device and were not well spread out, given the missing ground access in canopy covered areas. When overlaying the indirectly georeferenced maps with the movement tracks captured during the experiment described in section 7.2, the movement paths show high overlap accuracies with the accessible areas. Whether a hybrid approach was used or just the markers, it did not have a strong impact on the result if the image alignment was accurate. If GCPs are not an option, it is recommended to take several flights with varying flight pattern directions to counter systematic offset errors.

OpenDroneMap was tested as a free and open counterpart to Agisoft PhotoScan. The software runs on Linux operating systems and was therefore installed on a virtual Linux machine, hosted on the same laptop used for Windows based processing. While orthophotos could be generated from the image set acquired at the test site, larger data sets repeatedly caused the process to crash. The stage of scene reconstruction failed with a cryptic error message, which was identified as an out of memory problem by the online community. After increasing the memory of the virtual machine did not lead to any success, a new attempt was made by installing Ubuntu v16 on a desktop computer (Intel i5 3.2Ghz, 8GB RAM) in order to avoid memory allocation problems through the virtual machine. While the processing of larger datasets remained unsuccessful, it was possible to generate an orthophoto of Matoto, consisting of 187 images. However, the georeferencing stage crashed again due to an unresolved issue, which could be worked around by manually removing NAN altitude values from the file. Due to repeated issues, the OpenDroneMap software was evaluated as too premature to rely on, but given the active community, it might be promising in the future.

## 6.5 Summary

This chapter addressed Research Question 1: *How can appropriate base maps be created?* by exploring various hardware, software and flight execution configurations to find best practice solutions for aerial orthomap creation when operating in a scenario which lacks internet access, geographic reference points and has limited time and budget.

After introducing the choices of technical equipment and the implementation of various testing set-ups, the results were compared and discussed. The proposed solution is illustrated in figure 6.35. The GoPro camera, with its fast shutter speed, inbuilt intervalometer and wide angle lens performed well when the flight parameters were set to achieve a 90/30% endlap/sidelap combination. A script was developed to calculate the required speed and flight pattern parameters needed to obtain the desired overlap. The best georeferencing results were achieved using a handheld Garmin GPS device to capture GCPs where possible. The proprietary software Agisoft PhotoScan was able to correct for the GoPro's lens distortion and successfully align the photographs at a 90% endlap. Half of the photographs taken were omitted during the resource-heavy phase of scene reconstruction, resulting in a 80% overlap and a significant reduction in processing time.

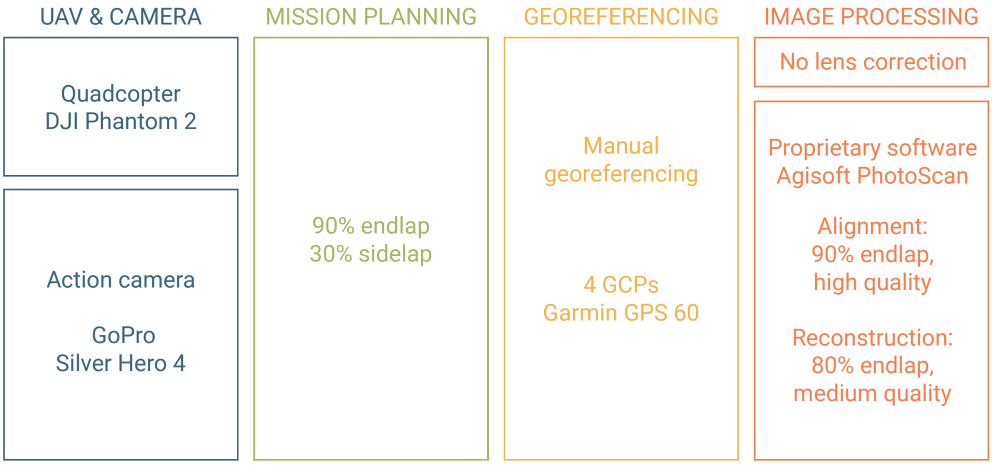



***Figure 6.35*** *Proposed processing pipeline*

***Table 6.14*** *Total estimated costs*

| | |
|---|---|
| Phantom 2, batteries (3x), Gimbal | £707 |
| GoPro Silver Hero 4 | £279 |
| Bluetooth Data Link | £130 |
| iPad mini 2 (optional) | £200 |
| GPS receiver | £270 |
| Agisoft PhotoScan (Commercial license) | £2731 |
| | TOTAL £4317 |

Table 6.14 indicates the total costs to realise the proposed solution. The prices shown reflect the amounts spent at the time of purchase. The GPS receiver used in this research to obtain GCPs was borrowed from the CIB and is not available for purchase anymore. A comparable, current Garmin model, GPSMAP 64 (Garmin, 2017), was used for the costs calculation as well as a commercial, single-user licence for Agisoft PhotoScan. The resulting total of less than £4500 is a one time investment to purchase the equipment and software, which allows for repeated use with low operational costs depending on logistics and other local circumstances. The laptop used for image processing is not included in this calculation based on the assumption that an organisation to carry out aerial mapping possesses standard work equipment, such as laptops. If that is not the case, another ~£1000 have to be added. It has to be recognised that in the Republic of the Congo such an expenditure exceeds an average person's annual income by more than 200% (World Bank

Group, 2016a). However, as demonstrated by this research project, international NGOs and academic institutions can usually afford amounts in that range.

At the time of writing, there have been developments in both hardware and software since the trials explained in this chapter. For instance UAVs have a increased flight time and inbuilt GPS-enabled cameras that produce higher resolution images. The principles set out in this chapter however still apply. While less flight might be needed to produce to cover a specific area. Sufficient overlap is required for SfM scene reconstruction. Bottleneck being the processing as SfM still very resource heavy and might even slow down with higher resolution images.

# 7 Map Understanding

Literature shows that humans can absorb billions of bits of information instantly if they are arrayed in a recognisable pattern within which each bit gains meaning in relation to all the others, e.g. a human face, or a galaxy of stars (Gregory, 1970; Gore, 1998). An orthophoto, much like any other photograph, is essentially a raster of colour values interpreted as segment of the Earth's surface by the human brain. Previous research carried out by Vitos et al. (2017), shows that Mbendjele hunter-gatherer communities prefer literal representations in icon design over abstract ones (see section 2.4.3). However, the view of the world available from aerial images is a view from above, and therefore unfamiliar to most people. Despite the availability of interactive systems, which allow the user to pan and zoom images, the map view remains essentially static as it is not possible to alter the viewer's vantage point (see section 3.2.3).

This chapter addresses the hypothesis that digital true colour orthophotos can be naturally interpreted by hunter-gatherers in the Congo Basin, although they have never seen their local environment from above. The assumption, as discussed in section 3.2.2 and indicated by previous research (Vitos et al., 2017), is that aerial images are easier to interpret than topographic maps since they are not abstract. Additionally, aerial imagery show points of reference (e.g. trees) even in rural scenarios where there are no features that are typically shown on a reference map (e.g. buildings, roads). The tasks in the experiment address RQ2: *To what extent are non-literate people able to understand maps and basic GIS interaction?*

Three experiments and methodologies are presented and discussed in the three following sections. Each of them aims to test aspects of whether aerial orthophotos are understood as a representation of well-known geographical landscape, even if participants have never seen the landscapes from that angle. For each of the three experiments, a bespoke app has been developed to run on an Android tablet. All of these fully function without the need of an internet connection and incorporate UAV generated reference maps using the methodology discussed in the previous chapter. Each of the experiment sections is named after the name of the apps: 'Image Tapper', 'Treasure Hunt' and 'Got it Right'.

The Image Tapper experiment, discussed in section 7.1, tests whether digital orthophoto maps can be understood and related to the real world through identification of known features. The Treasure Hunt experiment, discussed in section 7.2, tests whether abstract symbology overlaid on a reference map can be understood as location markers. In a game-like, immersive scenario, participants navigate to marked 'treasures' on a digital map. The Got it Right experiment, discussed in section 7.3, tests whether marked features on a map can be successfully corrected through the modification of marker location or symbology.

To avoid high-stress situations and interruptions by bystanders, encountered during the Image Tapper Experiment, two strategies to improve the testing experience were tested during the second field trip: immersion and separation. The first approach was to entirely omit the 'classroom situation' and instead turn the experiment into a Treasure Hunt game. Participants were encouraged to collaborate while performing the tasks while no researcher or research assistant was present. The following Got it Right experiment was carried out in a structured and supervised manner, but, with the research assistant taking participant away from the group to an isolated location. This way people could not interfere and the research assistant could more calmly explain the procedure, which resulted in a better experience.

The general methodology is to evaluate map reading performance based on success rates of given tasks during each of the experiments, with the threshold of success being defined in each of the sections. However, there is an underlying assumption based on the the work of Ormrod et al. (1988) and Kulhavy and Stock (1996) discussed in section 3.2.1, that people can meaningfully interpret maps without necessarily getting a 100% score. To test this hypothesis, both the accurate answers and the systematic errors that indicate that the map was understood as a concept are evaluated.

## 7.1 Image Tapper Experiment

This section describes the approach for testing whether remote communities with no prior exposure to cartographic representations can find familiar locations on digital, aerial orthophotos. After initially testing the approach by showing a single aerial photograph on a laptop computer, described in the following section, it became clear that a more structured data capture approach was required to make up for the difficulties in communication, which led to the development of the Image Tapper app.

The first camp visited during the January field trip in 2015 was Gbagbali (see Table 5.1), where the aerial image acquisition was trialled. The field site visits had to be organised in accordance with the schedule and obligations of the CIB staff as well as research requirements of the fellow ExCiteS researchers Michalis Vitos and Gillian Conquest (see section 8.2.4). When processing the aerial photographs, it turned out that there was not enough time to finish the orthophoto generation whilst still in the field, so that it could be demonstrated to the residents of the camp (see section 6.2.1). Thus, a single photograph that shows the entire camp and some of the surrounding forest area (figure 7.1) was presented to the local population. The photograph was taken using a camera with fish eye lens and therefore shows strong distortions towards the boarders of the image (see 6.1.4). Despite the lack of geographic accuracy, all topological relationships are maintained.

In order to analyse whether the residents could read the photograph in a map like fashion, a pilot study was carried out where participants were asked to point at predefined locations. During the process of image acquisition, Michalis Vitos carried out a usability experiment of the Sapelli UI with residents of the camp (Vitos et al., 2017). In this, the participants were asked to perform five practical tasks, where they had to collect data points for nearby resources. All of the selected sites were valuable resources for the community that they aspire to protect against damage from future logging activities, such as medicinal trees, the local cemetery and cacao trees. Each participant, accompanied by Michalis Vitos and two research assistants, walked to the selected sites where they were prompted to describe the point of interest and consequently map it using the Sapelli app.

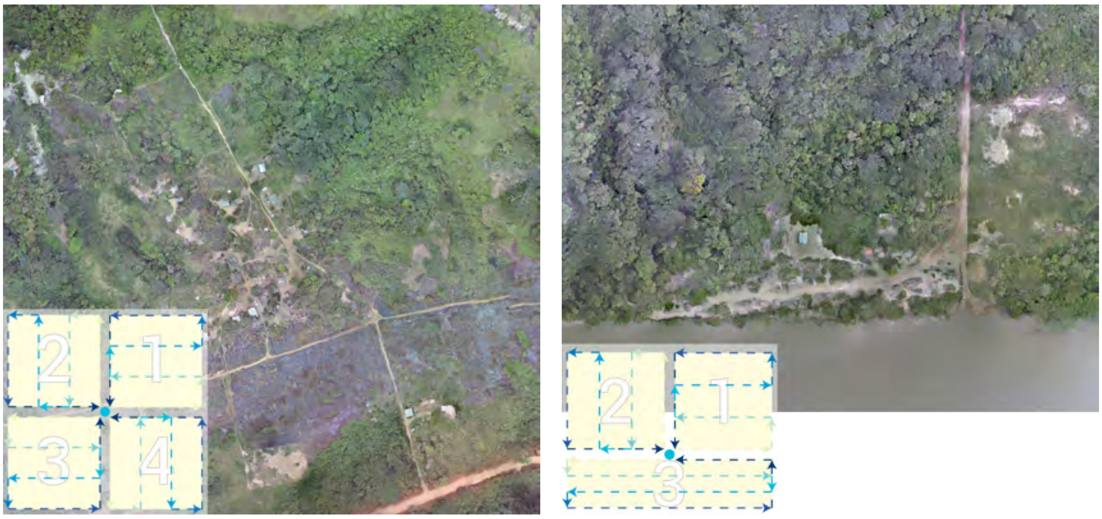
***Figure 7.1*** *Aerial photograph of Gbagbali*

Subsequent to this mapping exercise, ten of Vitos' participants took part in the pilot study for the mapping experiment. They were presented the aerial photograph opened in a graphics editor on a laptop computer. The research assistant in charge of translations named the previously mapped locations and for each of them asked the participant to point with their finger at the respective location on the screen so the researcher could mark the position.

In order to get insight into the thought process of the participants, the Thinking Aloud method, described in section 4.1.1 was encouraged. During the trial it became clear that the participants were too nervous or lacked contextual understanding to describe their actions. Even after a demonstration by the research assistant, none of the participants were willing to talk aloud and additionally they were hesitant to touch the laptop's screen. Instead they pointed in the area of the screen. Due to the vagueness of the participants' gestures, it was difficult to pinpoint it to a specific location on the photograph. Although most of the local residents seemed to point in the correct area, it was difficult to judge accuracy through pure observation given the imprecision in combination with the language barrier.

Following the tasks, the participants who took part in both Vitos' usability study and the map reading pilot experiment for this research, were invited to a semi-structured interview session. Vitos started the interviews by trying to facilitate a discussion on usability of and user satisfaction with the app UIs he had trialled, and to identify the reasons for some participants' poor performance on certain tasks. It soon became clear that the answers given by the participants were diverging from the observations made by the researchers. The participants, regardless of their performance, explained that they understood all tasks and had no problem completing any of them. Even after explaining the importance of their insights in order to make tools more usable, the participants showed clear discomfort talking about performance issues with the researchers. In addition to this problem, there is also the issue of language barrier. While it is common, when working across languages, that certain meanings get lost in translation, in this context, most words for the referred concepts do not exist in Mbendjele, especially in reference to the digital domain.

Informed by the pilot study, the need for a quantifiable method to analyse map understanding became apparent, which led to the creation of the Image Tapper app. With an app running on a tablet rather than a laptop computer, the participants are given the chance to manoeuvre the device more freely. The return to the base camp in Pokola was scheduled for a Thursday night. In order to use the remainder of the field time efficiently, visits of two nearby camps, Matoto and Sembola, were arranged with a driver and a communicator from CIB for the next day in order to capture aerial imagery in both locations. This way, the weekend, which is time off for all CIB staff, could be used to process orthophotos and to simultaneously develop the experiment app. The photos for the map production were captured in a single day using all seven available batteries. Four flights were carried out in Sembola and three in Matoto which resulted in the photo mosaics shown in Figure 7.2.



**(a)** *Sembola* **(b)** *Matoto*

***Figure 7.2*** *Orthophotos*

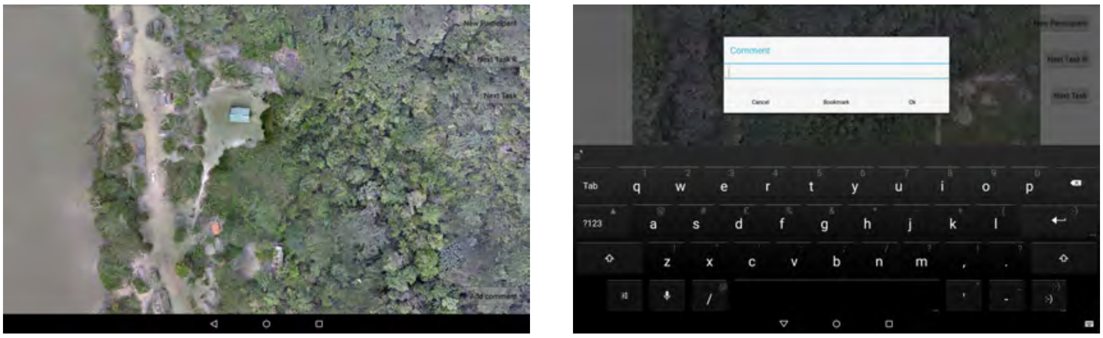
### 7.1.1 Image Tapper App

The experiment app (figure 7.3), termed Image Tapper, consists of one screen that automatically loads an image file from a specified path. If a valid file is found, a full screen version of that image is shown. Zoom and pan map interactions are enabled through two finger pinch and single finger drag gestures. Given that the north-alignment of maps is a learned convention in cartography, it was expected that people with no prior exposure to conventional maps would either physically align the map with the real environment or perform a mental alignment (Blades and Spencer, 1990).

The app was developed in Pokola over the course of one day. The internet connection, provided by CIB was limited but sufficient to identify and download an open-source project that supports zoom and pan gesture detection on an image view (Morrissey, 2016). Based on that framework, a rudimentary app was developed, consisting of a single screen that logs tap interactions. The captured data would be post-processed on return to the UK, to bring it into a suitable format for analysis, as described in section 7.1.3.

The experiment app shows an orthophoto of the village (figure 7.3a). The user can zoom and pan the map using the two finger pinch and drag gesture. On a single click event, a blue marker is added to show the indicated location. The user can correct the set location as long as the final decision is submitted by clicking a button to start the next task. The submitted location is written to a log file in the form of screen pixel coordinates along with a time stamp. An *Add comment* button was added in order to mark training records in the log files and to specify participant numbers (figure 7.3b).

Two variants of the app were designed to test whether the orientation of the image has an influence on the performance. The version with orientation change implements a 90 degree image rotation every time the *Next Task* button is tapped.



***(a)*** *Experiment UI* ***(b)*** *Comment UI*

***Figure 7.3*** *ImageTapper app UI*

### 7.1.2 Experiment Design & Procedure

The experiments were carried out in the camps Matoto and Sembola in northern Congo-Brazzaville. Matoto lies about 20km and Sembola less than one kilometre away from the logging town Pokola. Local communities speak either the locally spread Lingala, or their local Bantu or tribe language. Hence, the assistance offered by the company's staff was vital, since they spoke the local language and French to foster communication with the local population. CIB's social mapping team, like the vast majority in the country do not understand or speak English. During the field trip in 2013 an employee of the local radio station who speaks fluent English, French and Lingala, was recruited to assist with translations and research facilitation. Despite the researchers speaking French at a level of basic conversation, the decision was made to more comfortably discuss methodologies with the translator in English, to make sure that all instructions are understood correctly. On the downside, multiple steps of translation were required (e.g. English → French → Lingala → Mbendjele) and vice versa with the potential for meaning to be lost, changed or added.

The approach for engaging with communities and introducing tools was identical with the one applied during the scoping trip, described in section 2.4.3. Before visiting a community, the research assistants were briefed in conducting the FPIC process. It was their responsibility to introduce the project and ask the communities for the appropriate consent. In the field, the research assistants started with introducing themselves and the ExCiteS team to the communities. When the local population agreed to participate in training sessions and usability evaluation experiments, the research assistants engaged the crowd in training exercises, where they were first introduced to the Sapelli icons, printed on large flashcards followed by the research assistants handing over phones to teach the participants the navigation techniques. Assistance was provided to help people get comfortable with the way to 'tap' the images and move between screens. After the introduction and training session, participants were invited to take part in the experiments. In order to register, they were asked for their demographic information and whether they had ever seen a map or used a mobile device before. The research assistant wrote everything down.

The experiment to be carried out had the purpose to evaluate whether known features in the real environment could be successfully assigned to their according representations on the map. The process of choosing these features was a cooperative effort, which, in addition to the researchers Altenbuchner and Vitos and a research assistant, included a knowledgeable resident per village who volunteered to assist. The village inhabitant and the research assistant were asked to show the researchers close-by resources that are familiar to all village inhabitants. Decisions were made based on available icons in the Sapelli app as well as walking distances between the sites. The chosen features to be identified on the map are presented in table 7.1. Subsequent to identifying the task locations, the participants engaged in Michalis Vitos' usability evaluations of the Sapelli software. They were led to each of the identified locations and prompted to find and tap the right icons in the app (results published in Vitos et al. 2017). Similar to the pilot study carried out in Gbagbali, the same participants were then engaged in the map reading experiment on return of Vitos' data collection experiment.

***Table 7.1*** *Tasks per site*

| Task | Sembola | Matoto |
|---|---|---|
| 1 | Hut (own location) | Hut (own location) |
| 2 | Banana tree | Palm tree |
| 3 | Medicinal tree | Banana tree |
| 4 | Water source | Medicinal tree |
| 5 | Djengi (forest spirit) | Avocado tree |

In four days the mapping experiment was carried out in two locations, Matoto and Sembola (see figure 5.2), with 26 and 30 participants respectively, aged between 18 and 69 years old (M=30.21, SD=12.61). 32 of the participants had never seen a map before and 24 were either shown a map of Congo-Brazzaville in school or the 1:200000 scale map produced by the local logging company. The education level between the different villages varies with the distance from a logging town. In Sembola, which is in the direct neighbourhood of Pokola, 16 out of 30 participants have had formal primary school education and 6 people have attended college[4] for one or two years. In Matoto, 8 out of 26 people have attended primary school. Due to the limited amount of people living in the camps the sample size per location could not be extended.

After returning from the Sapelli mapping experiment the participants were, one by one, separated from the rest of the group and given the briefing for the map reading experiment. The set tasks for the participants were to first answer the question "what was shown on the screen?" followed by tapping on their current location as well as four previously mapped sites using the Image Tapper app running on a 10" screen Google Nexus tablet. For the process of the experiment, the research assistant was sitting next to the participant, either giving the tablet to them or holding it for them, as preferred by the participant. The research assistant obtained his briefing in English, which he passed on to the participant in the local language. The briefing was as follows:

> "What is shown here?"
> *Waiting for participant's answer.*
> *If answer incorrect:* "This is a map showing *name of village* from above."
>
> "During the experiment I will ask you to find specified locations on the map and tap on them with your finger. A marker will appear at the tapped location. You can change the marker position as often as you wish. Once you are satisfied with the position, tell me and we will continue with the next location. The experiment will be finished after setting the location of five locations. You are free to cancel the experiment at any point. Do you wish to continue?"

After giving their consent, the experiment started. At each location the participants were first asked what the image represents followed by the participants specifying their current location on the map and then four further resources. Half of the participants were given the app with static map orientation and the other half had rotation maps.

### 7.1.3 Post Processing

This section describes the process of retrieving the experiment data from the generated log files and bringing them in a shape that allows for efficient data analysis. Given the different image orientations when carrying out the experiment, a bespoke program was developed with the capabilities to project all coordinates in the same reference system.

For each participant a separate log file was created that contains the participant number, the tapped screen coordinates per task as well as optional comments, which were used to

[4] Equivalent to secondary school in UK school system

mark entries as test or experiment data. In order to analyse the data using various different software and to associate the captured demographic data with the results, a PostgreSQL database was created and populated with the last logged screen coordinate positions of each task, representing the marker positions before moving on to the subsequent task in the experiment.

In order to visually analyse the results of the experiment, a Python program was created that directly queries the database and visualises the coordinates transformed to match the same reference system. That means that the results are comparable, regardless of the image orientation during the experiment. The implementation of this coordinate viewer is built on the Qt Graphics View Framework (The Qt Company, 2016), which provides a surface for graphic 'items' and offers sophisticated coordinate system transformation functions. The framework defines three independent Cartesian coordinate systems that hold view coordinates, scene coordinates and item coordinates (figure 7.4) while offering functions that allow mapping between the reference systems.

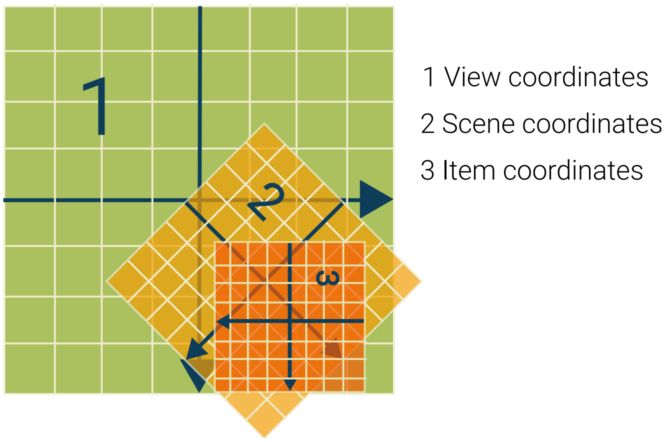



***Figure 7.4*** *Coordinate systems*

The 'view' resembles the screen or pixel coordinate system and has the purpose to visualise all contents of a 'scene'. The scene itself represents the logical coordinate system and serves as a container for graphic objects or 'items'. Transformations to the scene's coordinate system enables straight-forward implementation of responsive functions such as zooming and panning, while maintaining the inner logic of the reference system. The first item to be added to the scene is the back drop image. In order to project the tapped screen coordinates to the correct position on the image, rotation and translation transformations are carried out directly on the items' coordinate systems according to the rotation angle of the map during the process of data collection. The bespoke viewer is shown in figure 7.9 and its Python implementation can be found in Appendix A.5. In addition to visualising the orientation-corrected coordinates, a procedure was created to write these values back to the database. For this, the framework function to map coordinates between reference systems was used.

By visualising the coordinates as circles with 100 pixels diameter to control for tap inaccuracies (Hoober, 2015), each of the records was assigned a 'correct' value (TRUE or FALSE) depending on whether or not the circle overlays the according feature. Figure 7.5 visualises the different cases when locating a banana tree, showing correct classifications in greeen and incorrect ones in red.

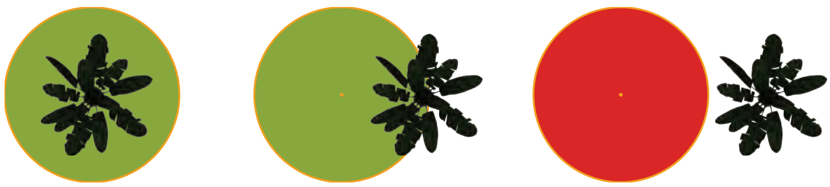


***Figure 7.5*** *Cases of correct / incorrect classification*

When visualising all data points labelled as incorrect most of the errors seemed systematic, which led to a sub classification of error types into the categories: 'similar feature', 'similar location', 'similar feature and location' and 'unclassified' if none of the above is applicable. Figure 7.6 shows an illustration of the different error types in relation to the correct feature shown in green. Similar feature is defined as the same type of tree (e.g. another banana tree) or object (e.g. another hut). Similar location means that the tapped point on the map is closer to the correct location than to any other site.

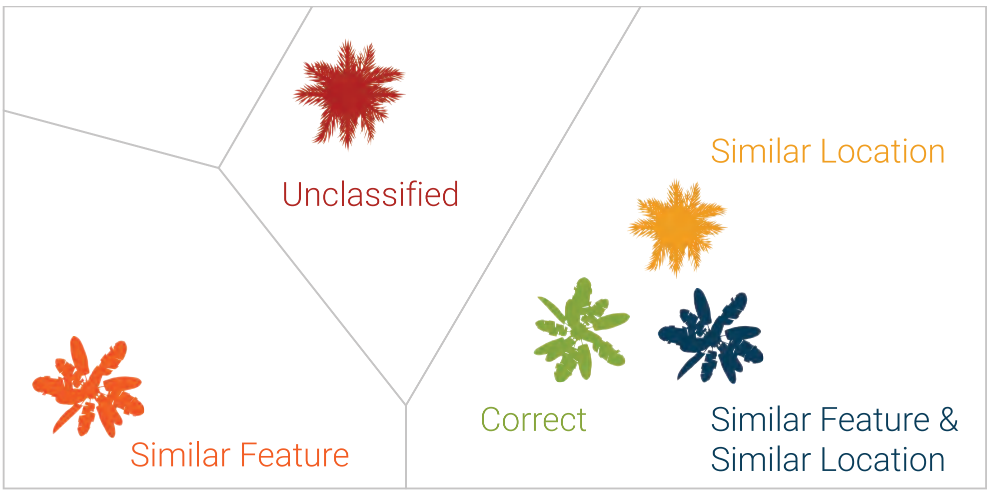



***Figure 7.6*** *Cases of error classification*

In order to obtain the polygons that define a 'similar location' according to the stated rules, Voronoi diagrams (Aurenhammer, 1991) were computed for both villages. A Voronoi diagram is a visualisation of two-dimensional areas that are divided according to the euclidean distance to specified sites. One such area represents all points that are closer to a specific site than to any other site.

A Python script was written to produce semi-transparent Portable Network Graphics (PNG) image format files to be overlaid on the image on the viewer. The algorithm follows the logic represented in Figure 7.7. The Python implementation of this algorithm can be found in Appendix A.5. As input, the algorithm takes the pixel coordinates of the five sites, a Red, Green, Blue, Alpha (RGBA) colour value per site and the image dimensions which define the size of the resulting Voronoi diagram. For each of the pixels in the photograph, the distances to each of the five sites are computed. Subsequently the pixel takes the colour value specified for the site with the shortest distance. The alpha value of each pixel is set to 100, which results in a transparency value of about 60%. Once each of the pixels have been processed and coloured, the image is saved. Sections of the resulting diagrams overlaid on the orthophotos are shown in Figure 7.8.

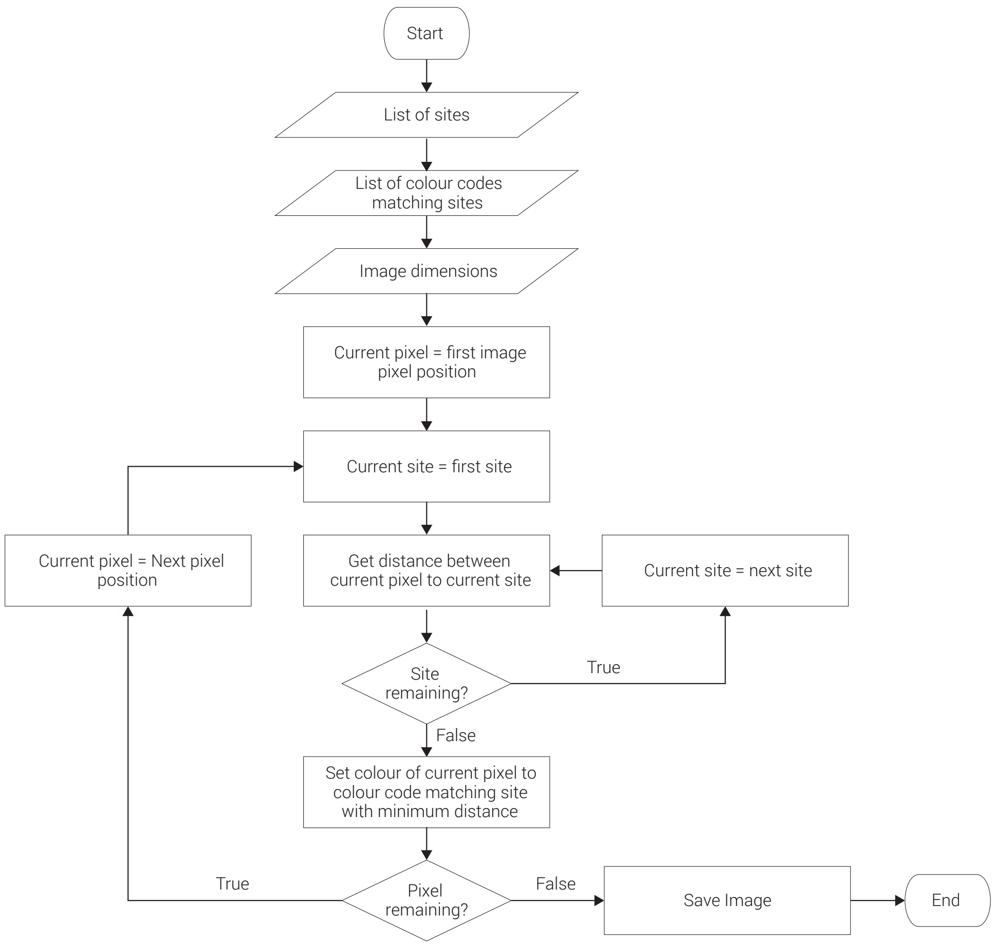
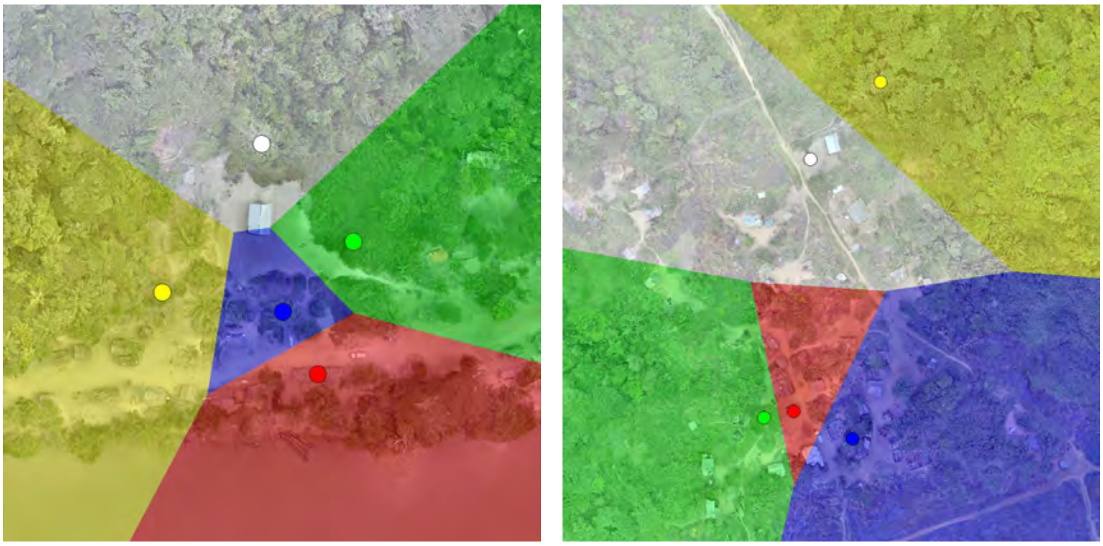



***Figure 7.7*** *Algorithm to compute Voronoi diagram*



*(a)* Matoto *(b)* Sembola

***Figure 7.8*** *Voronoi diagrams*

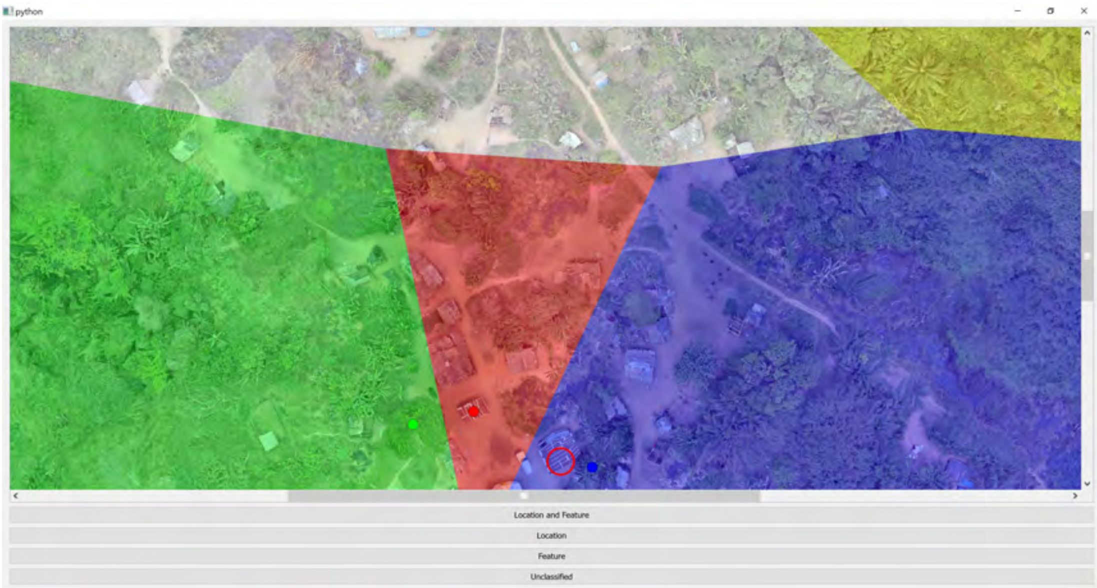



***Figure 7.9*** *Bespoke coordinates viewer*

For the final error classification, the viewer code was extended to overlay the semi-transparent Voronoi diagram on the map. Additionally, four buttons were added to write the error type back to the database according to the visual classification of each data point. Figure 7.9 shows the manual classification process of error types, by visually assessing whether the location and/or feature type were 'similar'. The resulting database table structure is shown in Figure 7.10, with the black headings indicating data retrieved from log files and demographic survey and the green headings representing values derived through post-processing.

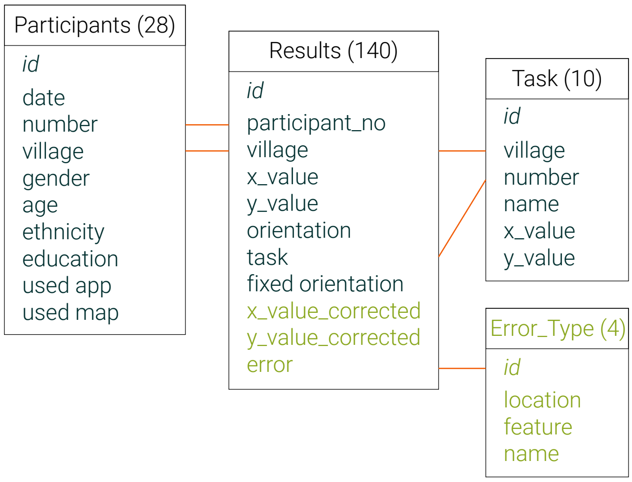



***Figure 7.10*** *Final database structure*

### 7.1.4 Results

Every participant gave a correct answer to the question on "What is shown here?". As shown in Table 7.2, 28 participants completed 140 tasks without image rotation, and 28 participants completed 140 tasks with fixed orientation. A task has been scored as correct if the user tapped directly on the targeted feature, or if the tapped location was less than 100 pixels away from the centre point of the target assuming the point was missed due to tap inaccuracy or due to wide fingers. When using the version with image rotation the participants performed 117 successful identifications (83.57%), while using the version without image rotation, they performed 113 successful identifications (80.71%). In both field sites, people scored insignificantly lower on fixed orientation. One out of 28 people aligned the tablet with the environment.

Table 7.3 shows the results of the error classification according to the method described above. In both locations, Matoto and Sembola, a total of 4 out of 52 (7.69%) unclassified errors were identified. A similar feature was chosen ten times (19.23%), and a position in a similar location as the sought-for location was tapped 15 times (28.85%). The most commonly identified error type was participants tapping a similar feature in a similar location, which occurred 23 times (44.23%) in total.

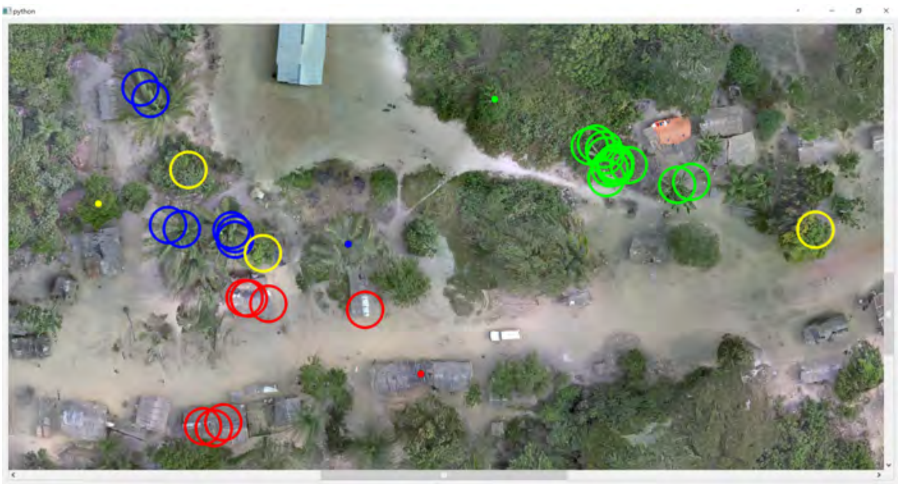
***Table 7.2*** *Success rate and orientation*

| Number of Tasks | | Success | | Failure | |
|---|---|---|---|---|---|
| 280 (100%) | | 228 (81.43%) | | 52 (18.57%) | |
| Rotation | Fixed | Rotation | Fixed | Rotation | Fixed |
| 140 (50%) | 140 (50%) | 117 (41.79%) | 111 (39.64%) | 23 (8.21%) | 29 (10.36%) |

*Table 7.3* Error classification

| Type | Count | Percent |
|---|---|---|
| Similar Feature | 10 | 19.23% |
| Similar Location | 15 | 28.85% |
| Similar Feature and Location | 23 | 44.23% |
| Unclassified Error | 4 | 7.69% |

Figures 7.11 to 7.13 illustrate the incorrectly tapped locations grouped by error types and site. The coloured dots indicate the locations the participants were asked to tap at and the hollow circles show the de facto tapped location with a 50 pixels radius. The colours illustrate the different tasks (task 1: red, task 2: blue, task 3: green, task 4: white, task 5: yellow)



***(a)*** *Matoto*

***(b)*** *Sembola*

***Figure 7.11*** *Similar feature errors*

In Matoto, 29 data points were classified as similar feature, of which 20 also fall into the category similar location. Most similar feature errors were made during task 3, when participants were asked to tap the location of a banana tree (see figure 7.11a, colour: green). 10 people tapped on the banana tree that is closest to the actual location and two people tapped on the banana tree next to that one. It is noteworthy that on the aerial photograph, the characteristic shape of the sought-for tree is difficult to make out due to shrubs that are surrounding the tree. Similarly, in Sembola, the task with the most errors in that category was the banana tree. Three people tapped a different but nearby banana tree (see figure 7.11b, colour: blue). Seven people in Matoto tapped on the wrong palm tree (colour: blue) and three people chose the wrong avocado tree (colour: yellow). When asked to tap on their current location on the map, seven people tapped on a different hut in Matoto (colour: red) and one person in Sembola (colour: red).

***(a)*** *Matoto*

***(b)*** *Sembola*

***Figure 7.12*** *Similar location errors*

The errors classified as similar locations are shown in Figure 7.12. In Matoto (figure 7.12a), there is a high overlap of errors that fall into both the similar feature and similar location category. Task three (banana tree, colour: green) has the highest error rate with 12 scores, with all classified results as incorrect for that task also falling into the category similar location. The runner up is task 1 (hut, colour: red) with ten points of which four also fall into the category similar feature. Task 2 (palm tree, colour: blue) has four scores, task 3 (medicinal tree, colour: white) has two scores and the task 5 (avocado tree, colour: yellow) has one score. In Sembola (figure 7.12b) there were two tasks that resulted in similar location errors. Six people tapped in a similar location as the sought-for banana tree (task 1, colour: blue) of which three were also banana trees and three people tapped in a similar location as the forest spirit 'Djengi' (task 5, colour: yellow).

***(a)*** *Matoto*

***(b)*** *Sembola*

***Figure 7.13*** *Unclassified errors*

Unclassified results are shown in Figure 7.13. In Matoto (figure 7.13a) there were three unclassified errors, one palm tree instead of the banana tree (task 3, colour: green) as well as a hut and a banana tree instead of the avocado tree (task 5, colour: yellow). In Sembola (figure 7.13b) one person tapped on a hut instead of Djengi (task 5, colour: yellow).

In Sembola, there were two tasks that every participant answered correctly, which are task 3 (medicinal tree) and task 4 (water source). The highest error rates were scored at tasks 1 (hut/own location) and 3 (banana tree) in Matoto with 50% of the participants tapping an incorrect location on the map followed by task 2 (palm tree), with an error rate of 30.77%. The total success rate in Matoto is 68.46% and 92.67% in Sembola.

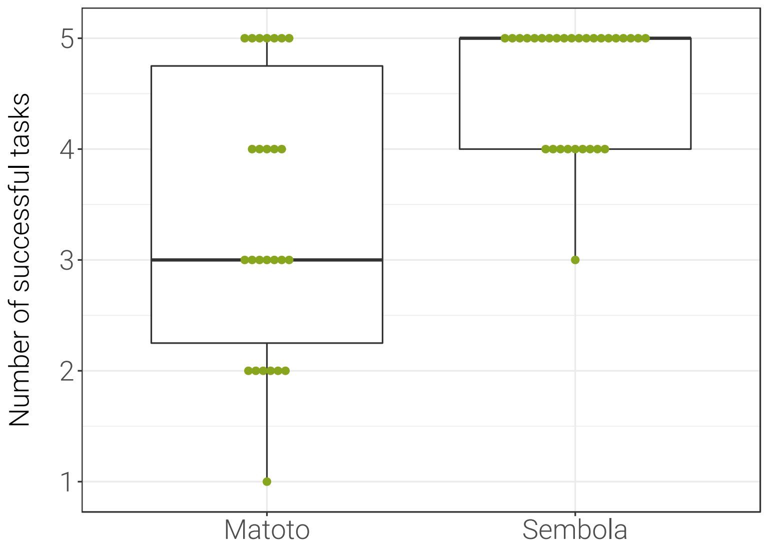



***Figure 7.14*** *Scores by village*

Figure 7.14 shows the distributions of score values per person in the villages Matoto and Sembola. With a median of 3 and an Interquartile Range (IQR) between 2.25 and 4.75, participants in Matoto performed worse than participants in Sembola whose median score value was 5 with an IQR between 4 and 5. Performing an unpaired t-test reveals that the mean increase in scores is statistically significant at a 95% confidence interval (p=0.00005804). The outcome suggests that the difference in means between the two villages is not due to chance and therefore the two villages are unlikely to consist of the 'same population' in a statistical sense. To explore the differences in populations that could have affected the results, demographic variables were tested against the scores. Figure 7.15 illustrates the number of successful tasks per person plotted against level of education (figure 7.15a), gender (figure 7.15b), whether they have seen a map before (figure 7.15c) or used a mobile app (figure 7.15d). Each box plot diagram compares the amount of successfully completed tasks with a specific demographic variable.

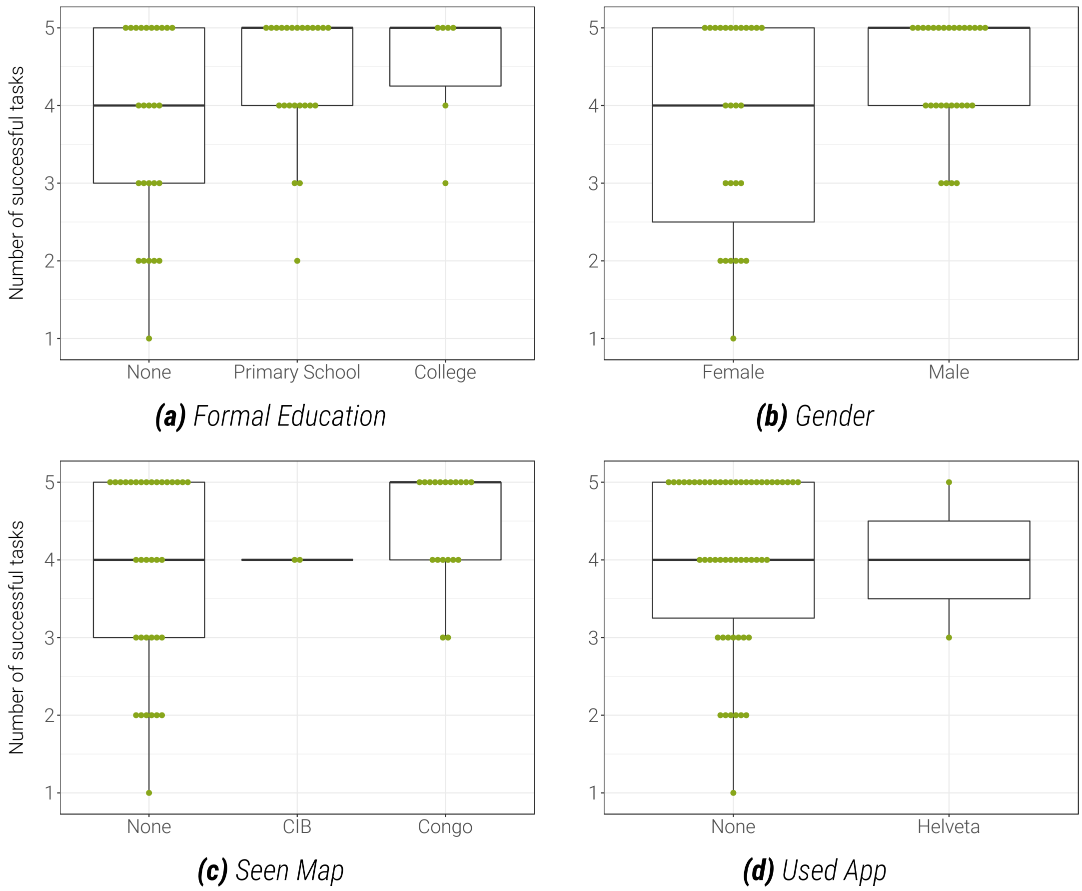



***Figure 7.15*** *Success rates and demographics*

26 out of 56 participants have not had any formal education, 24 have attended primary school for at least one year and six participants have attended college or a form of secondary school for one year or more. While there is a decrease in the number of participants moving to higher education, there is a clear trend suggesting a higher score for people who have gone to school for longer. The median for no formal education lies at 4 correctly scored tasks with an interquartile range from 3 to 5. Primary school attendants reach a median score of 5 with an interquartile range of 4 to 5 and college attendants reach a median score of 5 with a interquartile range of 4.25 - 5. An unpaired t-test confirms that the scores of participants who have never attended school and those who have are significantly different at a 95% confidence interval (p=0.02035).

Amongst the 56 participants were 27 woman and 29 men. Female participants scored lower, reaching a median number of successfully completed tasks of 4 with an interquartile range of 2.5 to 5. Male participants reached a median score of 5 with an interquartile range of 4 to 5.

Out of 56, 35 participants stated that they have never seen a map before. 19 people said that they have seen a map of the Republic of the Congo in school and two people were shown a map created by the logging company CIB. These were a result of the social cartography sessions, depicting protected resources overlaid on the 1:200,000 IGN base map described in section 2.3.2, Figure 2.8. The scores of participants who have never seen a map is similar to the result of participants who have never attended school due to the high overlap. For both, the median score is 4 with an interquartile range from 3 to 5. Similarly, people who have seen a map of the Congo have a high overlap with people who have attended school and therefore show a similar median score of 5 with a interquartile range of 4 to 5. The two people who were shown a map by CIB before both scored 4 out of 5.

Only two people stated that they have used a mobile app before which was the Helveta app developed in collaboration with Jerome Lewis as a forerunner of Sapelli, described in section 2.4.2. Their scores were 3 and 5. People who had not used a mobile app before reached a median score of 4 with a interquartile range of 3.25 - 5.

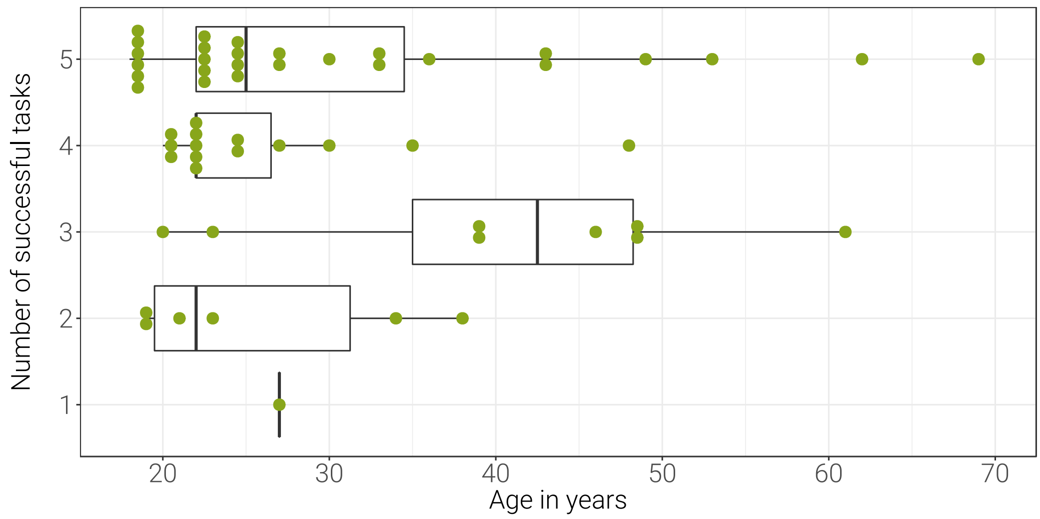



***Figure 7.16*** *Success rates and age*

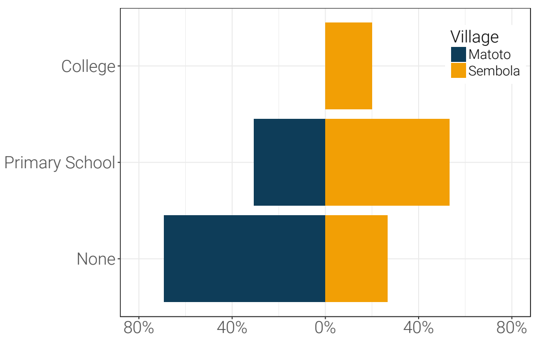
Figure 7.16 shows the number of successfully completed tasks in regards to the age of the participants. It reveals that the age median for the success scores 1, 2, 4 and 5 lie between 22 and 27 years whereas the median for the score of 3 successfully completed tasks lies significantly higher at 42.5 years (see figure 7.16).

### 7.1.5 Discussion

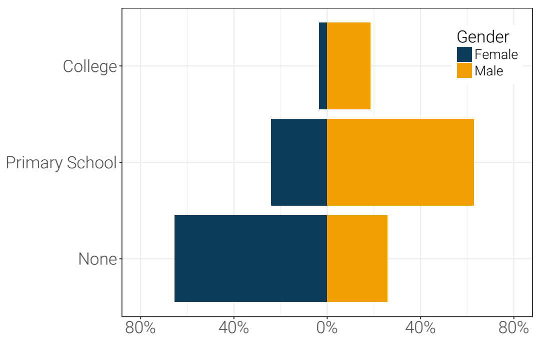
The results presented in the previous section show the that people who are not familiar with maps before could use and understand them without training. 81.43% of all tasks were successfully completed and 73.21% of all participants scored at least 4 out of 5 tasks correctly.

With 44.23% of all errors being a similar feature in a similar location as the sought-for location indicates that, potentially, with more training and less pressure the tasks could be completed successfully. Only a total of 7.69% of errors could not be classified. With the researcher as well as the translator being present when the experiment was carried out, participants often appeared insecure and under pressure which might have cause rushed responses with the intention to finish the task quickly. This issue is further discussed in section 8.2.1.

The alignment of the map had no influence on the performance and, except for one person, in Matoto, no participant attempted to align the map with the real environment. There is, however, a significant difference in performance related to the level of formal education. Those participants who went to school did generally better than those who had no formal education. Figure 7.17a shows that of all participants in Sembola, 20% attended college and 53.33% attended primary school compared to Matoto, where only 30.77% of the participants attended primary school. The reason for the higher level of formal education in Sembola is the close proximity to the logging town Pokola. This is most likely the decisive factor for the better overall success rate of the participants in Sembola compared to Matoto. Furthermore the results show that, in total, male participants scored higher than female participants. Looking at the proportion of women compared to the proportion of men who attended school, as shown in Figure 7.17b, reveals that there is a significant imbalance. 17.24% of male participants attended college and another 58.62% attained some primary school education. In contrast, only 3.7% of female participants went to college and 25% attended primary school. This leaves 70.37% of women without any formal education compared to 24.14% of men, suggesting that the difference in results based on gender is a spurious correlation (Simon, 1954).




***(a)** Education by village*




***(b)** Education by gender*

***Figure 7.17*** *Education by village and gender*

People who were shown a map of the Congo before also performed better than those who have never seen a map and those who were presented a map by CIB. It is noteworthy here, that all people who have stated that they have seen a map of the country before, when prompted, said that it was shown to them in class. The two people who stated that they were shown a map of CIB showed the same median as the overall results. Given the small sample of only two people it is difficult to draw conclusions here but it suggests that the overruling influence here is the education as opposed to the map.

Only two people stated that they have used a mobile app before. One scored 3 and the other one 5 out of 5 tasks correctly. The sample is too small to draw a meaningful conclusion. Furthermore, both participants said that the app they used was the Helveta app, developed by Lewis and Nelson (2006). They participated in the initial trial 9 years ago. One of the participants owns a mobile phone or has had extensive exposure to one but each of them have interacted with a smartphone during the introduction session and Sapelli usability study carried out by Michalis Vitos prior to this experiment.

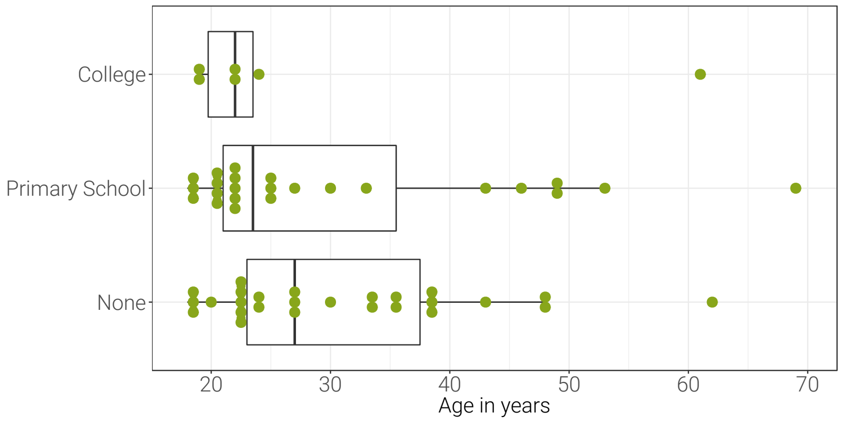



***Figure 7.18*** *Education by age*

Visualising distribution of age per score result, as shown in figure 7.16, reveals that participants younger than 35 dominate the top and bottom of the score scale while participants older than 35 performed better in the middle. Figure 7.18 shows that, in total, younger people have a higher level of formal education. However, unlike with gender, the effects of education on age can not be directly seen in the experiment results.

The Image Tapper experiment showed that most features (81.43%) could be successfully identified on a digital map. Participant observing revealed that some appeared nervous while carrying out the tasks and tapped at seemingly random locations on the map without focusing, supposedly wanting the experiment to finish sooner. For this reason the next experiment was planned as an immersive experience, excluding the possibility to 'shortcut' to the end, while omitting some of the stress through avoidance of direct participant observation.

## 7.2 Treasure Hunt

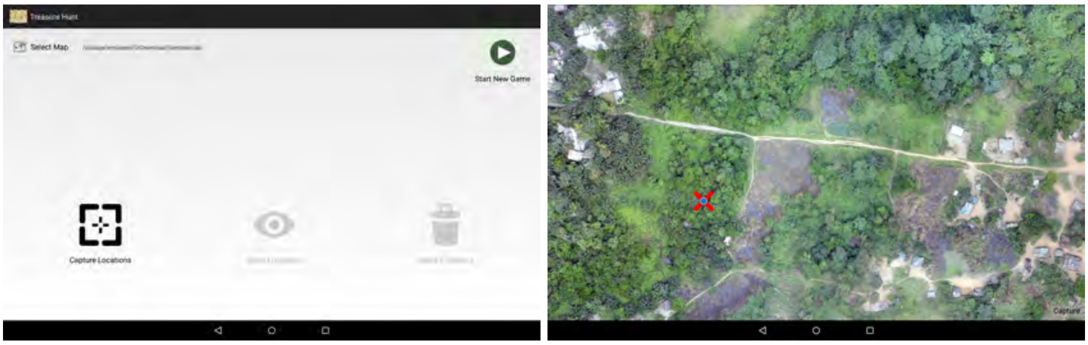
During the final field trip for this research, two map reading experiments were carried out with Mbendjele community groups. The first one of which was the Treasure Hunt, described in this section. While the Image Tapper experiment tested the understanding of the orthophoto map itself, the focus during the second field visit was whether the concept of symbology being presented on a reference map was understood. In cartography and GIS, the common representation of thematic maps is to overlay a reference map with abstract symbology representing information. In this case, all treasures are marked with a red cross symbol that should lead the participants to the treasures.

In addition, previous methodological issues were addressed in this experiment. During the scoping mission as well as the previous field visit it was noticeable that participants seemed to struggle with abstract tasks and they were stressed in exam like situations, which are common during HCI evaluations. Often participants were looking for the help of other community members, which had to be prevented by the research assistant to ensure valid results. The Treasure Hunt was chosen as an immersive experiment to address the need to find the task that both allowed the participants to work collaboratively and without supervision, as well as enabling their map interaction and understanding to be monitored. At the same time, the experiment allowed the evaluation of whether map interaction log files paired with GPS tracks would be sufficient to draw conclusions about map reading abilities, and therefore overcome the need of observing and interviewing participants.

The routes chosen by the treasure hunt participants were evaluated based on the assumption that people who understand the map of a known environment follow a logical route to collect the treasures. Examples of a logical route are the shortest overall path and the nearest treasure first path. It cannot be assumed, however, that participants applied the same logic. Therefore, additional evaluation metrics have been defined: routing strategy, shortest distance, off-track distance and off-track frequency. These metrics were tested across all participant groups to establish three levels of performance. In addition to the chosen routes, types of map interaction of each group were evaluated against the success levels to detect potential interaction patterns applied by high or low achieving groups.

### 7.2.1 Treasure Hunt App

The Treasure Hunt experiment app was developed specifically for this experiment to facilitate the objectives outlined above. The source code can be found in Appendix A.5. As shown in figure 7.19, the app incorporates a configuration mode for the researcher or game planner to configure the treasure constellation and set up a game as well as a game mode for the participants where the treasures are shown while all movements and interactions are tracked. The app has been deployed on a Google Nexus 10 device, running Android version 5.1.1. ArcGIS Runtime SDK for Android was used as a mapping framework due to offline capabilities. The app serves locally stored tile packages created from orthophoto maps (see chapter 6), following the documentation provided by ESRI, 2016.



***(a)*** *Configuration screen* ***(b)*** *Capture mode*

***(c)*** *Delete mode* ***(d)*** *Show mode*

***Figure 7.19*** *Treasure Hunt app*

**Administrator Mode**

The first screen presented to the user when opening the app is the admin configuration screen, which offers the option to set or change the path to a locally stored ESRI tile package that serves as a base map (figure 7.19a). Once a valid path is set, *Capture Locations* mode becomes available. In *Capture Locations* mode, the tile package is shown with the user's location indicated by a blue dot on the map (figure 7.19b). Pressing the *Capture* button on the lower right corner captures the current GPS coordinates as a treasure location and opens a camera view. Alternatively, if the user is not at the desired location, long-pressing a position on the map captures the according coordinates and similarly leads to a camera screen. The user has then the option to attach a photograph to the captured location. Finally a red 'X' is shown at the previously captured location on the map. This process can be repeated until all treasures are added. The *Delete Locations* and *Show Locations* modes become selectable when one or more locations have been captured. In *Delete Locations* mode the map is shown with all captured locations marked as a red 'X'. By clicking on any of the treasure locations, a dialogue window appears prompting the user to confirm the deletion (figure 7.19c).

**Game Mode**
Pressing the *Show Locations* button enters the game mode, which is designed for the participants of the Treasure Hunt. In this mode, all treasure locations are initially in view. Zoom buttons are displayed in the upper right corner showing a big tree and a small tree to represent the zoom in and zoom out functions for non technologically literate users. The map view can also be manipulated by one finger pan and pinch zoom gestures. In *Show Locations* mode, each map interaction is logged in a file together with the time stamp and the new extent and scale of the map view (figure 7.19d). Additionally the device's GPS coordinates are written to a log file during each Treasure Hunt run. In order to prevent users from accidentally closing the app, the *Back* button function can only be triggered if it is pressed quickly three times in a row. The *Home* and *Recent Apps* buttons were temporarily disabled through screen pinning, an Android feature that allows to create a single purpose device by locking an application to the screen.

### 7.2.2 Experiment Design & Procedure

Like the Image Tapper experiment during the previous field trip, the Treasure Hunt experiment was carried out at the two sites Sembola and Matoto. Due to the ongoing collaboration with the logging company CIB, the same research assistants could be recruited. Three school educated Mbendjele community members, who form CIB's social mapping team as well as the English, French and Lingala speaking employee of the local radio station. On first arrival at one of the villages, a research assistant introduced the team and the project in the local language. This was followed by a FPIC process as described in section 2.4.3. In both villages people were welcoming and eager to participate in the experiments.

At the beginning of every experiment day, people were invited to provide their demographic details to one of the research assistants and thereby sign up to participate in the experiments. Subsequently, male-only and female-only groups of four participants each were formed to team up during the Treasure Hunt. During the previous experiment, the participants seemed uneasy with having to solve tasks on their own while being observed in doing so. Beside the evaluation of treasure finding performances, another objective of this experiment was for the participants to familiarise themselves with the maps in a fun and stress-free situation. Thus, the task was to be solved in teams and without the presence of a researcher or research assistant. The participant's GPS locations and interactions with the device were logged, which build the basis for data analysis.

Figure 7.20 illustrates the procedure of a Treasure Hunt run. To prepare a run, the researcher together with one local research assistant identified four locations, placing two treasures at each of them (figure 7.20a. The treasures were cardboard stars in varying colours. Using the Treasure Hunt app, a photograph of the treasures was taken at each location to be able to easily find the locations of missing treasures, if necessary.

After the research assistants finished the set-up for a specific run, the app was switched to *Show Locations* mode and a research assistant explained the app's UI, the map interactions and the rules of the game to the participants (figure 7.20b).

> "The aim is to find the star at each of the marked locations on the map. Even if there are two stars, just take one at each location. When you have found all four treasures, return to the start. The order in which you find the treasure does not matter. You can move the map like this *drag gesture*, move closer to the ground like this *zoom in button* or this *pinch gesture*, move further away from the ground like this *zoom out button* or this *pinch gesture*. You are free to cancel the experiment at any point. Do you wish to continue?"

On return of the first group, a second run was carried out by the opposite gendered group before changing the treasure constellation, avoiding the participants informing each other about the locations. Subsequently the participants were sent off with the task to return one treasure from each location (figure 7.20c).

***(a)*** *Treasures set-up* ***(b)*** *Participants briefing* ***(c)*** *Return*

***Figure 7.20*** *Treasure Hunt experiment procedure*

An initial pilot run of the Treasure Hunt with four male and four female volunteers was carried out in Sembola to refine the procedure which was applied in all runs. In the test run, the groups were given the instructions to return to the starting point after picking up a treasure before moving on to the next. It has been decided against this method for the reason that it would take too much time. The same participants were needed to carry out the experiment described in the following section 7.3. Given their hunter-gatherer lifestyle many of them still wanted to go to the forest for subsistence provision before dusk. The time requirements for the follow-on experiment were much shorter than the Treasure Hunt and did not practically affect plans to go after forest activities. Yet, it was important to not discourage participants from continuing after the Treasure Hunt.

### 7.2.3 Post Processing

Over a period of six days, the Treasure Hunt experiment was run 20 times in two villages. For each Treasure Hunt run a location log file (listing 2) and an interaction log file (listing 3) was recorded. The location files contain the date and time of each location update followed by the location itself as obtained by the Android framework: name of the provider that generated this fix, latitude in degrees, longitude in degrees, estimated accuracy in metres, time of this fix since last system boot, altitude in metres, velocity (if applicable) in metres per second.

**Listing 2** Location log file extract

```
2015-12-03 14:30:18.095, Location[gps 1.405383,16.328844 acc=6
   et=+2d1h17m11s188ms alt=325.30361683183975 vel=0.989469],
2015-12-03 14:30:25.102, Location[gps 1.405395,16.328822 acc=6
   et=+2d1h17m18s196ms alt=326.41850375634374 vel=1.0820967],
2015-12-03 14:30:28.099, Location[gps 1.405392,16.328803 acc=6
   et=+2d1h17m21s194ms alt=327.2477319437114 vel=0.7596696],
2015-12-03 14:30:31.111, Location[gps 1.405404,16.328776 acc=4
   et=+2d1h17m24s199ms alt=328.1260427818063 vel=1.2915652],
2015-12-03 14:30:33.104, Location[gps 1.405415,16.328746 acc=6
   et=+2d1h17m26s191ms alt=328.56888110729324 vel=1.2176585],
```

Whenever a user interaction with the device occurred in *Show Locations* mode, the date and time were written to the log file along with the type of interaction (zoom or pan), the map scale and the values for longitude in degrees and latitude in degrees of each of the four corners that make up the rectangle of the current screen extent. In order to efficiently analyse the data and connect to it via various software packages described in the following sections, a PostgreSQL/PostGIS database was created. The structure is illustrated in figure 7.21.

**Listing 3** Interaction log file extract

```
2015-12-03 14:23:19.105, Pan, 1421.5658155660947,
   16.32744031965709, 1.4045554751197606,
   16.330229910434635,  1.4045554751197606,
   16.330229910434635, 1.4061943597015687,
   16.32744031965709, 1.4061943597015687,
2015-12-03 14:23:19.323, Pan, 1421.5658155660947,
   16.327437594782257, 1.4045431279849443,
   16.330227185559803, 1.4045431279849443,
   16.330227185559803, 1.4061820125667523,
   16.327437594782257, 1.4061820125667523,
2015-12-03 14:23:20.855, Zoom, 2198.3488919312776,
   16.326686866625398, 1.4041496957616562,
   16.331000767345017, 1.4041496957616562,
   16.331000767345017, 1.4066841124344334,
   16.326686866625398, 1.4066841124344334,
```

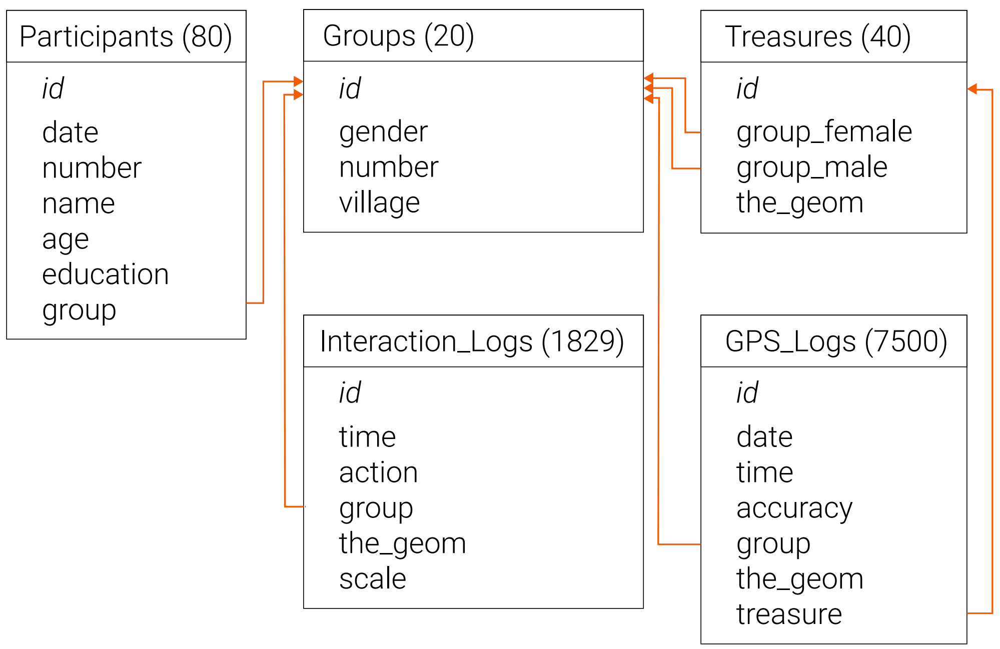



***Figure 7.21*** *Database structure for Treasure Hunt*

GPS coordinates were captured by the device whenever a fix was obtained by the tablet, while map interactions were logged each time an interaction was registered by the device. In order to relate the participants' location with map interactions, they needed to be synchronised. To achieve this, Views were created for each Treasure Hunt run, breaking down the data to a second interval. The missing data were imputed using a Last Observation Carried Forward (LOCF) strategy implemented in SQL. Figure 7.22 illustrates the logic of the LOCF data interpolation.

| PKey | Time | Geometry |
|---|---|---|
| 1 | 10:23:19 | POINT(16.328921 1.405251) |
| 2 | 10:23:21 | POINT(16.328904 1.405269) |
| 3 | 10:23:26 | POINT(16.328892 1.405283) |
| 4 | 10:23:27 | POINT(16.328881 1.405309) |
| 5 | 10:23:31 | POINT(16.328879 1.405316) |

a) Logged data

| PKey | Time | Geometry |
|---|---|---|
| 1 | 10:23:19 | POINT(16.328921 1.405251) |
| 2 | 10:23:20 | POINT(16.328921 1.405251) |
| 3 | 10:23:21 | POINT(16.328904 1.405269) |
| 4 | 10:23:22 | POINT(16.328904 1.405269) |
| 5 | 10:23:23 | POINT(16.328904 1.405269) |

b) View of interpolated data

***Figure 7.22*** *LOCF logic*

Figure 7.22a represents example location data logged by the device. Figure 7.22b shows a view of that data after the interpolation. In that, a primary key of consecutive numbers is generated matching the row numbers of the table. The time column in the data view represents a time series starting with the earliest logged time of a Treasure Hunt run and ending with the latest. The time interval in between rows are one second. A left outer join achieves that all logged geometries are matched to the according time stamp leaving the rest blank. A LOCF function fills in the blank cells by copying the previous observations iteratively until the next one is reached.

**Listing 4** LOCF in PostgreSQL after Vogler (2015)

```
CREATE AGGREGATE locf (GEOMETRY) (
   SFUNC = locf_s,
   STYPE = GEOMETRY
);

CREATE OR replace FUNCTION locf_s (a GEOMETRY, b GEOMETRY)
   RETURNS GEOMETRY LANGUAGE sql AS
   'select coalesce(b, a)';
```

Listing 4 shows how LOCF was realised by applying a coalesce function vertically across rows in a table (Vogler, 2015). Coalesce is a built-in function in PostGIS (PostgreSQL Global Development Group, 2016) that takes any number of arguments and returns the first one that is not NULL. A locf aggregate function (line 1) was defined that iterates over each input row and calls the state transition function locf_s (line 6). This returns the value of the current cell or, if it is NULL, the value of the previous cell (lines 7-8). The same procedure has been applied to captured interaction data, carrying forward geometry and map scale values to fill in the gaps.

**Route Construction**

To carry out analysis on routes chosen by the participants, route networks were generated in a post-processing step followed by the calculation of the optimal route and the nearest treasure route. The optimal route describes the shortest overall route from the starting point to all treasures and back to the starting point. The nearest treasure route follows the path of the nearest remaining treasure until all locations are visited and then returns to the starting point. Distance calculations for these analyses are based on Network Theory due to the fact that villages and forests are only easily passable on a network of paths. A network consists of a set of nodes, some or all of which are connected through edges of known lengths. For finding the shortest path between two nodes in a network, Dijkstra's algorithm is commonly used (Dijkstra, 1959). He describes the generation of a shortest-path tree – the least cost path from one node to every other node, with exactly one path connecting two single nodes.

In both study sites, Sembola and Matoto, paths are not fully detectable from the aerial image and therefore the following method was applied in order to generate a network used for distance calculations.

The first step towards building a network graph was the creation of a paths layer illustrated in figure 7.23. The input for the generated network were all GPS locations recorded during the Treasure Hunt. The geographic coordinates, which are based on a spheroid model of the Earth, were projected into a UTM (Zone 33) reference system in order to facilitate and speed up geometry calculations [1]. Next, the Points layer was transformed into a Polyline layer by connecting the coordinates of each group ordered by time, so each Treasure Hunt run is represented by one line [2]. In order to have have parallel lines collapse into one path, a buffer zone was created with a distance parameter of 3 metres, which turned out to be a good fit for both datasets, Sembola and Matoto. The boundaries of resulting buffer polygons were dissolved into one polygon to get rid of overlapping areas [3]. In preparation for the following step the vector layer was converted into a raster layer by assigning the value one to each pixel lying within the polygon geometry [4]. A thinning algorithm after (Zhan, 1993) was applied in order to obtain linear features with the width of a single cell [5]. The resulting lines were finally converted back into a Polyline vector format by extracting linear features from the thinned raster layer and converting them into lines [6]. The resulting Polyline feature serves as a base for creating a network graph.

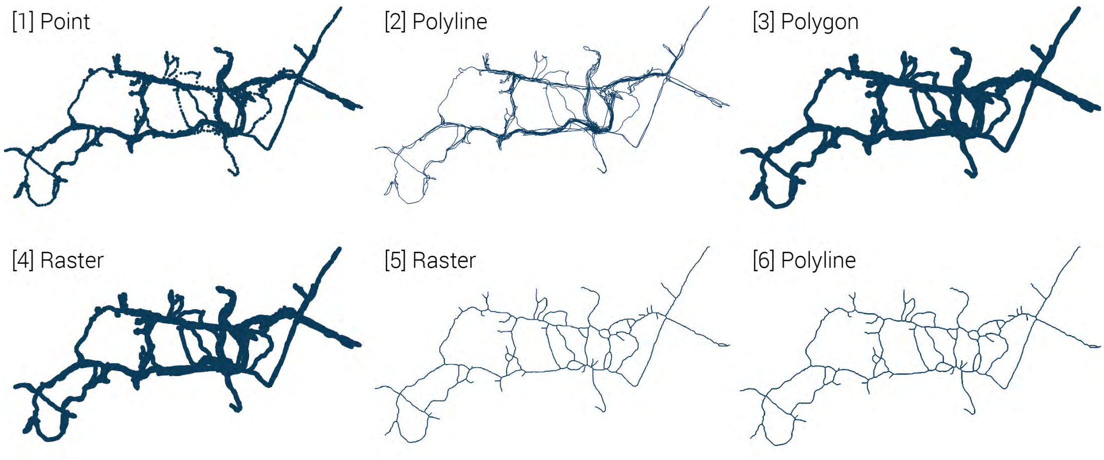



***Figure 7.23*** *Path generation (Sembola)*

In order to generate a network graph the polylines need to be 'noded'. This is achieved by splitting the roads into segments at all intersections and nodes are created at each of those. This approach assumes that any segment can be reached from any other segment via the intersections.

**Nearest Treasure Route Algorithm**

An algorithm was developed to calculate the shortest route to all treasures following the strategy of always choosing the closest treasure as the next destination (listing 5). The algorithm was implemented in Python using QGIS libraries, which can be found at Appendix A.5.

In order to carry out distance calculations along the paths, a network topology was built as a first step (line 4). Making use of the QGIS Network Analysis Library (Project QGIS, 2016a), a graph was created consisting of edges and vertices. All paths are treated as bi-directional and the cost of a journey is purely defined by the length of a path. Since the treasures are not located exactly on the paths, they are matched to the nearest path segment for distance calculations.

In order to find the closest treasure from the starting point, the shortest distance after Dijkstra was calculated from the starting location to all remaining treasures (line 8). The generated distances were then compared to each other (lines 9 - 10) with the shortest being appended to the order of treasures (line 11). Consequently the closest treasure was removed from the list of treasures and become the new starting point (lines 12-13). After all treasures were put in the correct order, the result was written to a vector layer and loaded into QGIS for visualisation.

**Listing 5** Nearest Treasure algorithm

```
1  INPUT: fromPoint, treasures, paths
2  OUTPUT: orderTreasures
3
4  GENERATE networkGraph FROM paths
5
6  WHILE COUNTER IS LESS OR EQUAL TO AMOUNT OF treasures
7     FOR EACH treasure IN treasures
8        CALL dijkstraDistance WITH (fromPoint, treasure)
9        IF NEW DISTANCE IS LESS THAN PREVIOUS DISTANCE
10          closestTreasure ← treasure
11    APPEND closestTreasure TO orderTreasures
12    REMOVE fromPoint FROM treasures
13         fromPoint ← closestTreasure
14
15 FUNCTION dijkstraDistance(pointA, pointB)
16    GENERATE tree FROM pointA TO ALL REACHABLE NODES IN networkGraph
17    startVertex ← FIND pointA IN networkGraph
18    currentVertex ← FIND pointB IN networkGraph
19    WHILE currentVertex IS NOT startVertex
20       ADD DISTANCE BETWEEN VERTICES TO accumulatedDistances
21    SET currentVertex TO PREVIOUS VERTEX IN tree
22    RETURN accumulatedDistances
```

For the distance calculation (lines 15-22) a tree is generated with the shortest paths from the starting point to all other nodes using the dijkstra method in the QGIS Network Library. To acquire the shortest distance between two points the tree is traversed backwards, adding up the lengths of the edges until the starting point is reached (lines 20 - 22).

#### Optimal Route Algorithm

The optimal route is understood as the shortest route possible, to visit each treasure location. This route can be computed by solving the so-called Travelling Salesman Problem, which is a classic problem in the field of graph theory. Much research has been dedicated to maximising efficiency in finding the shortest closed route when visiting a set of locations exactly one time (Punnen, 2007).

Heuristics approaches, in which the selection of the next location is based on a set of rules, are often used to increase performance and to guarantee a solution after a certain amount of iterations (Bartholdi and Platzman, 1982; Helsgaun, 2000).

pgRouting, an extension for PostGIS/PostgreSQL database, provides a travelling salesperson function, which is an approximation algorithm based on Euclidean distances (pgRouting Contributors, 2016). In order to compute an exact solution, a brute force algorithm is required, which means that all options are tested and compared. Given that the start position is known and each route can be travelled in the reverse direction, the number of cases to check is $\frac{(n-1)!}{2}$. Given a Treasure Hunt scenario with four treasures, the number of permutations to check equals 12, which is feasible in terms of computational power and does not require the use of heuristics. In order to obtain accurate results based on network distance, a brute force algorithm was implemented in Python (see Appendix A.5) following the algorithm outlined in listing 6.

Similar to the Nearest Treasure Algorithm, a network topology consisting of nodes and edges was created as a first step (line 4). Next, a distance matrix was generated by calculating the Dijkstra distance between each pair of treasures (lines 6 - 9) using the same algorithm as described in Listing 5 (lines 19 - 26).

In order to test various options that make up a valid route, all permutations of the treasures including the starting point were computed. Subsequently the list was reduced to those variations with the starting point as the first element (lines 11-12).

Distances are then computed by going through each permutation and creating the sum of the paths lengths between the treasures, stored in the distance matrix (lines 15 - 16). Finally the permutations with the shortest distance are selected and added to the order of treasures, ready for visualisation. Given that each route can be traversed in reverse order the result contains a minimum of two variations.

**Listing 6** Travelling Salesman algorithm

```
INPUT: fromPoint, treasures, paths
OUTPUT: orderTreasures

GENERATE networkGraph FROM paths

FOR EACH treasureX IN treasures
   FOR EACH treasureY IN treasures
   distanceMatrix[x, y] ← CALL dijkstraDistance(treasureX, treasureY)
   distanceMatrix[y, x] ← distanceMatrix[x, y]

FIND ALL PERMUTATIONS FOR treasures
REDUCE LIST TO PERUMTATIONS STARTING WITH fromPoint

FOR EACH PERMUTATION IN PERMUTATIONS
   SUM UP DISTANCES BETWEEN TREASURES FOUND IN distanceMatrix

orderTreasures ← FIND COMBINATIONS WITH SHORTEST DISTANCE IN DISTANCES

FUNCTION dijkstraDistance(pointA, pointB)
   GENERATE tree FROM pointA TO ALL REACHABLE NODES IN networkGraph
   startVertex ← FIND pointA IN networkGraph
   currentVertex ← FIND pointB IN networkGraph
   WHILE currentVertex IS NOT startVertex
      ADD DISTANCE BETWEEN VERTICES TO accumulatedDistances
      SET currentVertex TO PREVIOUS VERTEX IN tree
RETURN accumulatedDistances
```

### 7.2.4 Results

One of the Research Questions addressed by the Treasure Hunt experiment is whether people who possess good spatial knowledge of an environment can intuitively read and use a high-resolution orthographic photo of that environment and whether they can navigate to positions marked by abstract symbols overlaid on the map. Therefore various measures of success were defined and evaluated. In addition, this section explores the way that participants interacted with the map through analysis of the log file. As and aid for the analysis of the Treasure Hunt experiment, video files were generated that show the participants' GPS location and their current map extent at each point of the run in accelerated motion. The files can be found in Appendix A.5 as well as online under the url: http://bit.ly/treasurehunt-videos.

A total of 22 runs have been carried out by eleven groups consisting of four male participants and eleven groups consisting of four female participants. The first two groups (f1, m1) were pilot groups to test and refine the methodology. During the second round, the research assistant in charge of the participant briefing sent off the male group before the female group had returned. As can be seen on the timed GPS tracks, the two groups teamed up while looking for the treasures and are therefore excluded from further analysis. The log records of teams m3, f4, m7 and f8 are incomplete due to either a loss of GPS signal during the run or an unintended closure of the app by the participants or through technical failure. The following analysis section is based on the produced GPS and interaction logs of the groups listed in Table 7.4.

***Table 7.4*** *Valid runs*

| | **Sembola** | **Matoto** |
|---|---|---|
| **Female** | f3, f9, f10, f11 | f5, f6, f7 |
| **Male** | m9, m10, m11 | m4, m5, m6, m8 |

All groups were successful in finding and returning a complete set of four treasures between 12 and 42 minutes. In order to further compare the groups' performances, four quantitative measures of success were taken into consideration: the routing strategy, the distance of the travelled route compared to the optimal route, the sum of distances the group went 'off-track' and the amount of treasures approached on a direct way.

**Routing strategy**

Literature suggests that in the absence of knowledge of the shortest overall route, people presented with the task to navigate between a set number of locations tend to move to the nearest unvisited location until all have been visited (Vickers et al., 2003; Lihoreau et al., 2012). While both taking the shortest route and the nearest neighbour route suggest that the locations on the map were understood and could be associated with their real locations, an analysis was carried out to asses whether such a routing strategy was applied by the participants. In order to compare the taken routes with both strategies, algorithms described in section 7.2.3 were applied to calculate mentioned routing strategies for each treasure constellation. For the nearest treasure and optimal route computation, the algorithms described in listings 5 and 6 were run in the Python Shell of QGIS loading the resulting routes as vector layers for each treasure constellation.

The Shapefile to PostGIS Import Tool (Project QGIS, 2016b) was then utilised to save the routes to the Treasure Hunt database. The results were overlaid with the actual routes taken by each group and visually compared.

***Table 7.5*** *Routing strategy results*

| | Group | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| **Male** | – | – | SR | SR/NT | SR | – | SR | SR | SR/NT | SR |
| **Female** | – | NT | – | SR/NT | SR | None | – | NT | SR/NT | None |

SR = Shortest Route, NT = Nearest Treasure Route

Table 7.5 shows the routing strategies applied by the participants. The options are Shortest Route (SR), Nearest Treasure Route (NT), None and Error (–). Shortest Route means that the order of treasure locations returned by the algorithms described in listing 6 was chosen. Nearest Treasure means the participants were following the path of the nearest remaining treasure based on their current location (listing 5). A combination of both indicates that the route of the nearest treasure was the same as the optimal route. None means that a random or non-categorised path was followed and error indicates that either GPS signal was lost during the run or the group accidentally left the applications and was unable to re-open it.

An identified routing strategy does not necessarily imply that the participants necessarily followed the shortest path as defined by Dijkstra all the way. The measure is solely based on distance and does not take into consideration other factors, such as level of path accessibility. On several occasions, groups temporarily diverted from the computed path to choose a free route over a forest route. Sometimes the chosen route paths were only minimally longer than the computed route, such as choosing the left or right path to circumvent an obstacle. To account for these cases, the order of found treasures was taken as a determining factor instead of the paths segments.

12 out of the 14 valid runs followed one of the above defined strategies. While all male groups chose either the Nearest Treasure or the Shortest Route, two of the female groups' chosen routes deviate from those. Female group 7 started out following the Optimal Route but missed the second treasure. After collecting the remaining ones they went back to pick up the missing treasure before heading back to the starting location. Female group 11

equally started out following the Optimal Route. After finding two treasures they lost the marked treasure locations from their map view and thereafter seemingly wandered around without a clear target until they eventually found all treasures.

Three groups were heading in the wrong direction for a limited amount of time. Male group 4 took a wrong turn and headed in the wrong direction for about 15 minutes. Both male and female group 6 had difficulties finding the last treasure. The male group walked past it and headed too far north until they realised after 120 metres, turned around and found it on the way back. The female group made a wrong turn at the intersection and looked for the treasure too far south.

**Travelled distance compared to optimal route**

This section takes into account the length of the travelled route compared to the optimal route which equates to the shortest possible route (see section 7.2.3). The assumption is that a shorter travelled route indicates better map understanding. An SQL query was applied to output the travelled distance compared to the optimal distance per group. The logic and implementation of this query can be found in Appendix A.3

| Group | Female | Male |
|---|---|---|
| **3** | 0.97 | – |
| **4** | – | 1.94 |
| **5** | 1.02 | 0.9 |
| **6** | 1.41 | 1.47 |
| **7** | 1.94 | – |
| **8** | – | 1.38 |
| **9** | 1.16 | 1.04 |
| **10** | 0.8 | 0.82 |
| **11** | 2 | 1.07 |

***Table 7.6*** *Travelled / shortest route*

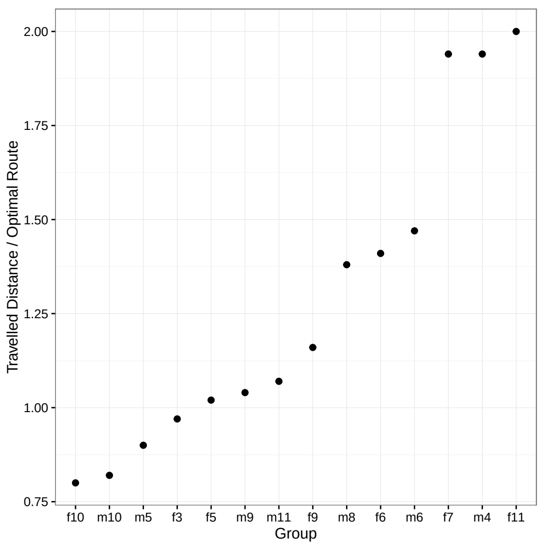



***Figure 7.24*** *Travelled distance*

The results are shown in Table 7.6. The values are the representation of the total route length divided by the length of the shortest route, rounded to two decimal numbers. Groups f10, m10, m5 and f3 show a value smaller than one, which is due to the recorded GPS tracks not leading all the way up to the treasures. Since all groups returned all treasures it is assumed that one or more group members went to get the treasure while the rest of the group remained on the path closer to the next treasure. Figure 7.24 shows a plot of the travelled distance per group ordered by distance. Three clusters can be distinguished. Eight groups chose a route up to 25% longer than the shortest possible route, 3 groups' travelled distances lie between 38 - 47% added to the optimal route, three groups' distances are with 94% - 100% approximately twice as long.

**Off-track**

Detours are defined as the travelled segments leading away from the next treasure, given that these segments do not follow the shortest path after Dijkstra (1959). For each GPS fix in the logs, the distance between the current position and treasure is compared to the preceding fix's position in regards to the treasure location. As long as these distances consecutively increase, the group is considered to be walking away from the treasure location. An SQL query was applied to obtain the off-track route paths. The logic and implementation of this query can be found in Appendix A.4

The results were manually post processed to eliminate the route segments leading away from the treasures but are part of the optimal route. For this, the route segments were loaded into QGIS and overlaid with the optimal routes for visual comparison. A computation of this last step was not possible in a straightforward manner, given that the optimal route follows the interpolated network path (see section 7.2.3) and does not exactly overlap with the chosen path.

The query results are shown in Table 7.7. The values represent the sum of all off-track route segments per group in metres as well as the amount of times a group went off-track. The distance values range between 0 - 281.82 metres of total off-track distance. The frequency show a variation between 0 and 14 times. Figure 7.25. shows a correlation plot of the total distance and frequency values. A trend line is shown as well as the 95% confidence interval. The groups with no off-track route segments are missing from the plot. For the remaining groups, three clusters can be distinguished. Groups m11, m9 and m8 show small distance values between 0 and 48.66 metres and small frequency values between 1 and 5. Groups f6 and f7 achieved distance values of 154.16 metres and 167.23 metres and they went off-track 11 and 7 times. The highest off-track results were achieved by groups f11 and m4 in both distance and frequency with values of 281.82 metres, 246.68 metres and 14 times. Two outliers lie outside the 95% confidence zone. Group f9 achieved a low total off-track distance of 47.43 metres but took a wrong turn 9 times. Group m6, on the other hand, went off-track 7 times but stayed on the false route for a total of 190.21 metres.

| | Distance | | Frequency | |
|---|---|---|---|---|
| **Group** | Female | Male | Female | Male |
| **3** | 0 | – | 0 | – |
| **4** | – | 246.68 | – | 14 |
| **5** | 0 | 0 | 0 | 0 |
| **6** | 167.23 | 190.21 | 9 | 7 |
| **7** | 154.16 | – | 11 | – |
| **8** | – | 48.66 | – | 5 |
| **9** | 47.43 | 32.29 | 9 | 3 |
| **10** | 0 | 0 | 0 | 0 |
| **11** | 281.82 | 30.3 | 14 | 1 |

***Table 7.7*** *Off-track distance (metres)*

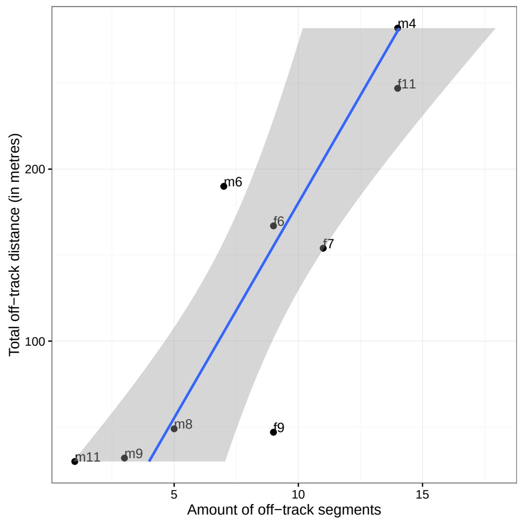



***Figure 7.25*** *Off-track correlation*

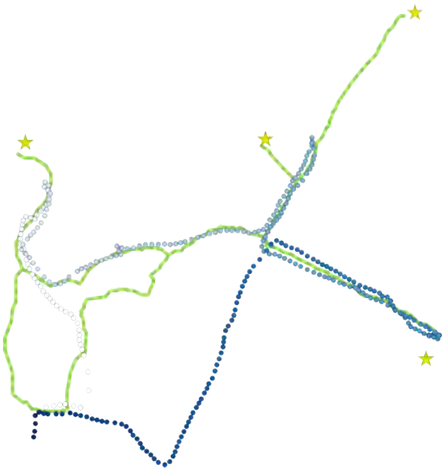
The rating ignores the way back from the last treasure to the starting point because all of the groups chose a direct way, resulting in a scale from 0-4. The 5 groups with no off-tracks route segments achieved the highest rating of 4. Three teams diverged from a direct route on the way to one treasure location. Four groups found half of the treasures directly and two groups found one treasure on a direct way.

#### Overall success ratings

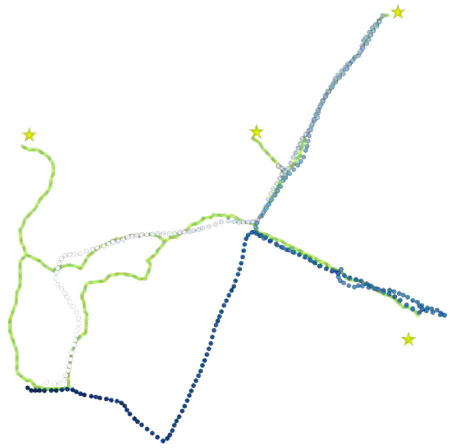
Taking into consideration all measures of success as defined above, five out of 14 groups (f3, f5, m5, f10, m10) consistently achieved the best results taking into account all measures of success described above. Six groups (f6, m6, m8, f9, m9, m11) walked a distance less than 1.5 the length of the shortest route, approaching at least two of the four treasures on a direct route. Three groups (m4, f7, f11) walked a way almost twice the optimal route. Two of these groups followed no apparent logical order in collecting the treasures and only reached two treasures on a direct way. The third group had the biggest detour with 181.82 metres. The groups were categorised into three groups: perfect, minor problems and major problems. A perfect run means, that no detours were made. At the same time, these groups that had the lowest values for travelled distance rating and all of them seemed to follow a routing strategy (see figure 7.26). The category 'minor problem' contains groups that have not taken a wrong way at an intersection more than twice and their travelled distance was less than 1.5 times the shortest route (see figure 7.27). The category 'major problems' are the groups that approached only one treasure on a direct way and whose travelled distance was almost double the shortest route (see 7.28). The results show no difference in performance by gender.

***(a)*** *Group f5 (Matoto)*

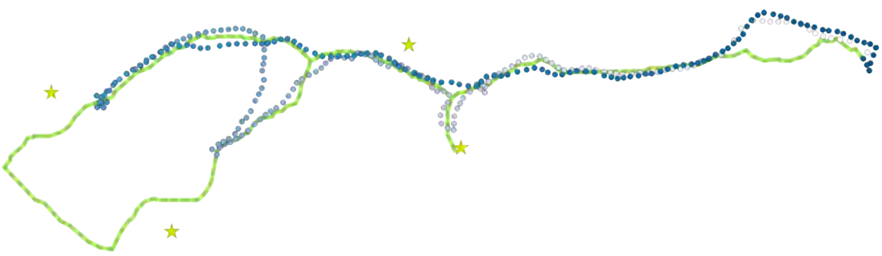
***(b)*** *Group m5 (Matoto)*



***(c)*** *Group f10 (Sembola)*

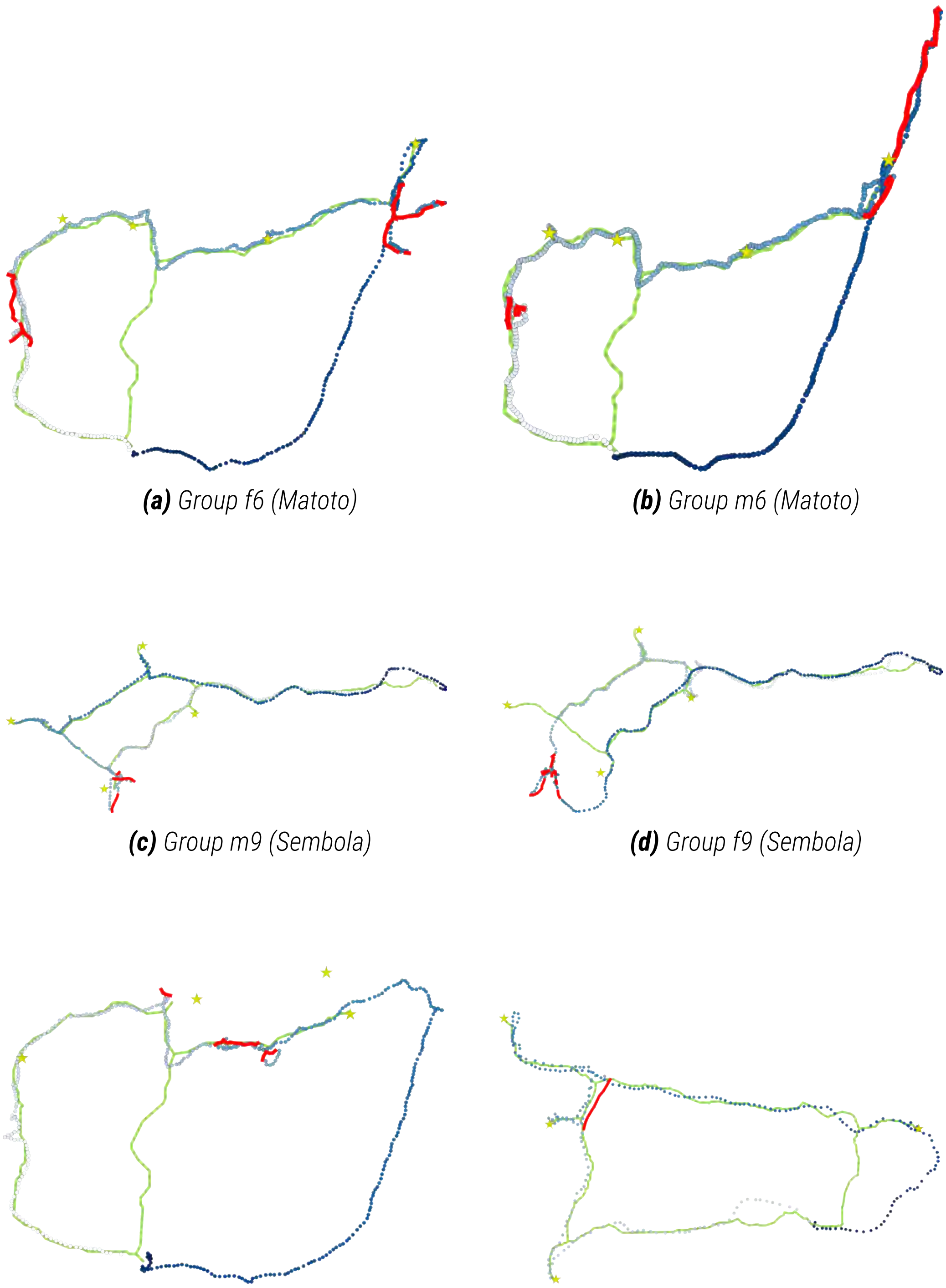


***(d)*** *Group m10 (Sembola)*



***(e)*** *Group f3 (Sembola)*

***Figure 7.26*** *Perfect*

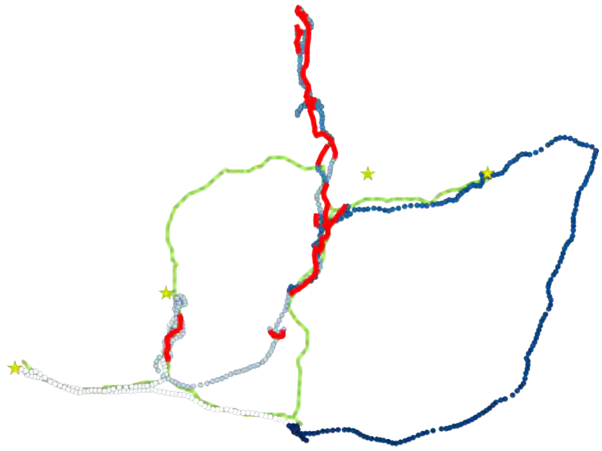


*(a)* Group f6 (Matoto) *(b)* Group m6 (Matoto)

*(c)* Group m9 (Sembola) *(d)* Group f9 (Sembola)

*(e)* Group m8 (Matoto) *(f)* Group m11 (Sembola)

**Figure 7.27** Minor problems



*(a)* *Group m4 (Matoto)*

*(b)* *Group f7 (Matoto)*

*(c)* *Group f11 (Sembola)*

***Figure 7.28*** *Major problems*

**Map Interaction**

The map interaction log file the app created per Treasure Hunt run provides insights into how the various groups used the app while searching for treasures. This section looks into map interaction and presents results in comparison to previously defined success levels and demographic factors of participants.

Quantifying the total number of map interactions is difficult due to the the way that finger drag and pinch gestures are implemented by Environmental Systems Research Institute Inc (ESRI)'s (2016) mapping API used in the Treasure Hunt app. Depending on the length and speed, an interaction could be logged once or multiple times. Regardless of implementation, it is a matter of definition whether a one finger drag (or pan) or two finger drag (or pinch) gesture counts as one or several interactions. To avoid this problem, a temporal visualisation has been chosen that illustrates interaction behaviour without giving total numbers.

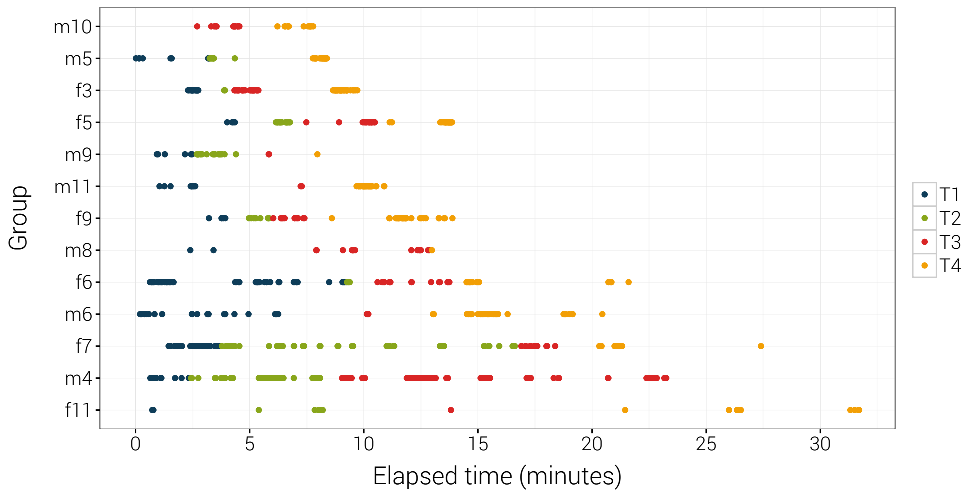



***Figure 7.29*** *Temporal pattern of map interactions*

Figure 7.29 presents the temporal pattern of map interactions per group. Each of the points represent a user action logged to the device, which triggered either a pan or zoom function. The different colours represent the number of the treasure the group was approaching while interacting with the device. The groups are ordered by least travelled distance relative to the shortest possible distance, with the distance increasing in direction top to bottom. For group f11, which took the longest time to complete the Treasure Hunt, the visualisation shows an evenly distributed interaction pattern but few interactions in total. The two other groups who had difficulties in finding the treasures (m4, f7) show much more interaction with the device at all four stages. Looking at the groups with minor problems, shown in Figure 7.27, the interaction patterns consistently show high activity for the stages when groups were off-track (f6: T1, T4; m6: T1, T4; m9: T2; f9: T3; m8: T3) except for group m11 who does not show any activity for when they were off-track (T2).

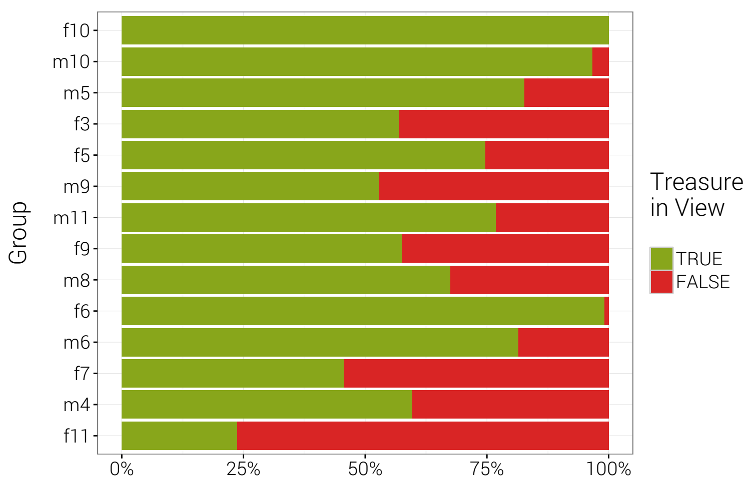
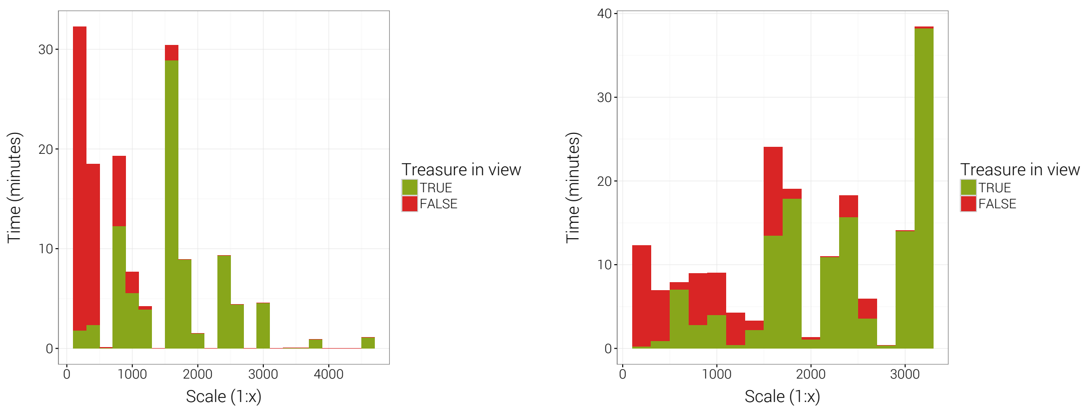



***Figure 7.30*** *Time treasure in view*

Figure 7.30 shows the percentage of time, per group, that the sought-for treasure locations were visible in the current map view. The groups are ordered by least travelled distance relative to the shortest possible distance, with the distance increasing in direction top to bottom. The expected outcome was that groups that performed better showed a higher percentage of time having the treasure in view. The results show a recognisable trend confirming this expectation, with two outliers (f3, m9) showing less time of treasure visibility than expected as well as two outliers (f6, m6) showing more time of treasure visibility than expected.

The groups f6 and m6, had the sought-for treasure in view 99.17% and 81.4% of the time and both groups seemingly had difficulties finding the exact locations of the first and last treasures. The highest result of 100% treasure visibility was achieved by group f10, which did not interact with the map and therefore had all treasures in view as default.

Group m9 seemingly only used the map when approaching the first two treasures. Afterwards they continued the search but the map view remained on treasure number two. Once on the way to treasure number 3 and equally on the way to treasure number 4, a brief panning interaction happened which did not move the treasure towards the map view and might have been accidental touch events while walking. Group f3 was performing well despite a treasure visibility of only 57.03%. The group seems to have memorised the fourth treasure location. They walked to the correct area and only when close to the treasure, panned the map to the correct location. Additionally, group f3 used large map scales, which increases the likelihood of losing the treasure out of view due to the smaller extent shown at once.




***(a)*** *Sembola* ***(b)*** *Matoto*

***Figure 7.31*** *Time per map scale*

Figures 7.31a and 7.31b both show the cumulative time that all participants remained at specific map scales, indicating whether the treasure they were looking for was in view (green) or not (red) at a bin width of 200 scale levels. A separate visualisation is shown for each village to account for the varying minimum scale levels, which were defined by the size of the tile package in the Treasure Hunt app.

The range of possible scales for Sembola lies between 1:194 and 1:4689. It is clearly visible that large map scales increase the likelihood of the sought-for treasure being out of view. In Sembola, the participants spent a total of 50 minutes 54 seconds on large map scales ( < 1:700) but only 9% of that time (4 minutes 12 seconds) was the treasure in view. The largest cluster of chosen map scales while the treasure was in view is detectable between 1:1500 and 1:2000 (in view: 39 minutes 20 seconds, out of view: 1 minute 31 seconds). In total the map scales when the treasure was in view seems nearly normally distributed with sharp break intervals.

In Matoto, the range of possible map scales lies between 1:194 and 1:3126. There are four visible clusters 1:500 - 1:1100, 1:1500 - 1:1700, 1:2100 - 1:2700 and 1:2900 - 1:3126. Most time was spent on the smallest possible scale 1:3126, where the groups remained for 31 minutes 1 second in total. When overlaying the diagrams for each village in form of a density plot, as shown in Figure 7.32, the same four clusters are apparent. While participants in Sembola preferred map scales between 1:1500 - 1:2000, participants in Matoto overwhelmingly used the smallest map scale of 1:3126.

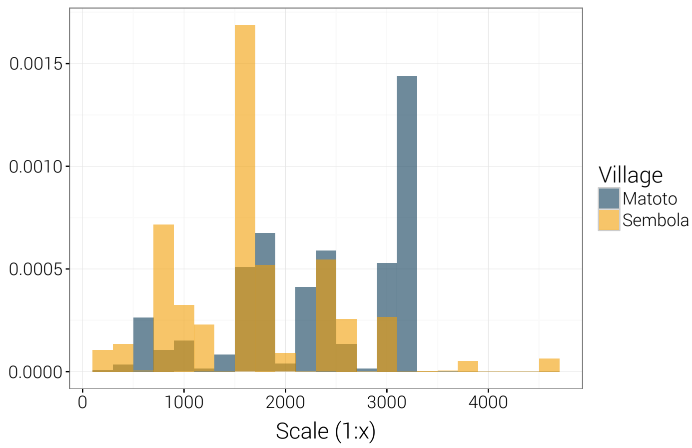
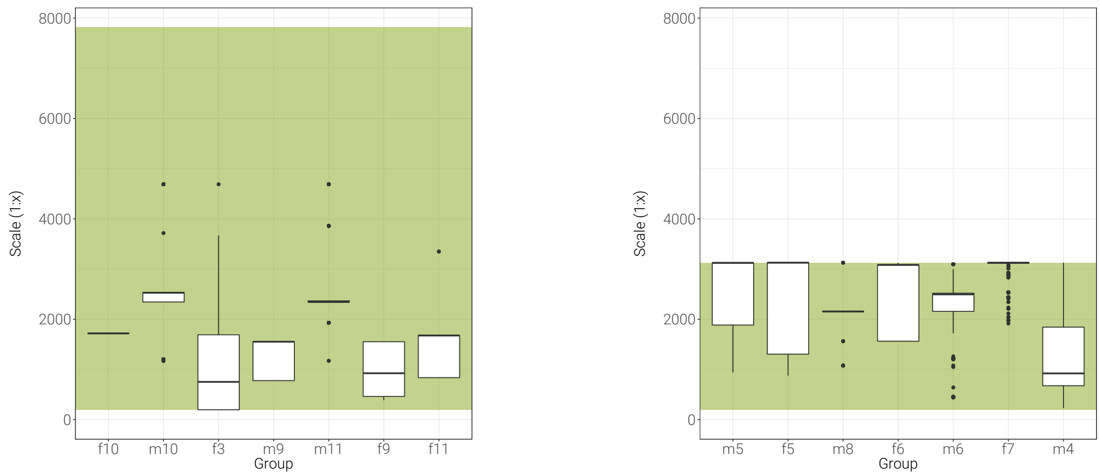



***Figure 7.32*** *Normalised density plot comparing scales*

To determine whether the use of specific map scales show a correlation with the success of a groups, two box plot diagrams were produced, indicating the distribution of used map scales per group, for Sembola (figure 7.33a) and Matoto (figure 7.33b) . The groups are ordered by least travelled distance relative to the shortest possible distance, with the distance increasing towards the right. The green colour indicates the range of possible scales. It is remarkable that participants in Sembola, who had a greater variety of scale levels, spent more time on large scales than participants in Matoto, who where restricted by the minimum scale being 1:1:3126. Otherwise, no trend in preference of map scale usage could be detected.



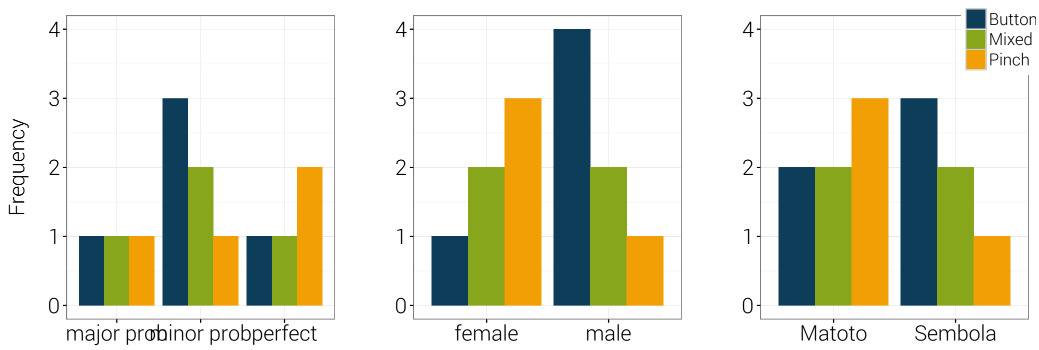

***(a)*** *Sembola* ***(b)*** *Matoto*

***Figure 7.33*** *Scale distribution, ordered by success*

To analyse whether the type of zoom (pinch gesture or button) shows a correlation with success, gender or village, three bar charts, (shown in Figure 7.34) were created. Due to the difficulties in quantifying zoom interactions, as discussed above, measure for these graphs are whether a group used exclusively button zoom, pinch zoom or a mix of both. The results are shown in Table 7.8.

***Table 7.8*** *Type of zoom per group*

| Button zoom | Pinch zoom | Mixed | None |
|---|---|---|---|
| f11, m5, m8, m9, m11 | f3, f5, f7, m6 | f6, m4, f9, m10 | f10 |




***(a)*** *Success* ***(b)*** *Gender* ***(c)*** *Village*

***Figure 7.34*** *Zoom types by success group, gender, village*

Five out of 14 valid groups exclusively used the buttons for zooming the map in and out. Four groups used the two finger pinch gesture, four groups interchangeably used both and one group did not zoom the map at all. Figure 7.34a shows that in each of the success groups, there are teams who used button zoom, pinch zoom and mixed. The same holds true for gender (figure 7.34b), however, only one female group used button zoom on its own, two groups used both and three groups used the pinch zoom. In male category, four groups used the button zoom, two groups used both and three groups used the pinch zoom indicating that female groups had a preference for the two finger pinch zoom while male groups predominately used the button zoom. Figure 7.34c shows that in both villages there are groups who used button zoom, pinch zoom or mixed both. No clear preference could be identified.

### 7.2.5 Discussion

Every group returned all treasures, which confirms that the participants were able to independently read the maps and understand basic symbology. Despite differences in performance, none of the groups went off in completely different areas from where the treasures were placed. In order to further quantify success and detect where specific groups were struggling, the taken routes were compared with two routing strategies and additionally the travelled route was compared to the computed shortest route. Given that this measure only takes into account route lengths and no other qualities, such as ease of access, further measures of success were taken into account to guarantee more robust results. Off track distance, or detours were computed as well as the frequency in which a group went off-track. The results show that five out of 14 groups consistently achieved the best results taking into account all measures of success. Six groups showed some problems in finding the direct route to one or two treasures and three groups walked almost twice the lengths of the optimal route while showing major problems. No difference in performance by gender could be detected.

As all measures of success are based on routes extracted from the GPS log files shown in listing 2, the quality of the GPS locations has an influence on the assessment of success. Four groups' results could not be analysed for the reason of incompleteness, which was potentially due to loss of GPS signal failure during the run or an unintended closure or due to technical failings of the app, which also illustrates a downside of unsupervised experiments, where the researcher does not have a chance to intervene.

In order to judge the quality of the location readings, accuracy of the GPS fixes was taken into consideration as well as the distances between two consecutively recorded GPS fixes. Estimated horizontal accuracy readings are provided by the Android framework for each location fix (Google, 2016). In their documentation, Google (2016) describe that it is assumed that location errors are random with a normal distribution and the estimated accuracy represents one standard deviation. No further information is provided as to how the accuracy estimation is calculated.

| Accuracy | Count | Percent single | Percent cumulative |
|---|---|---|---|
| 3 | 1 | 0.02 | 0.02 |
| 4 | 2215 | 38.35 | 38.37 |
| 6 | 2425 | 41.99 | 80.36 |
| 8 | 931 | 16.12 | 96.48 |
| 12 | 180 | 3.12 | 99.6 |
| 16 | 18 | 0.31 | 99.91 |
| 24 | 4 | 0.07 | 99.98 |
| 32 | 1 | 0.02 | 100 |

***Table 7.9*** *Accuracy of GPS fix*

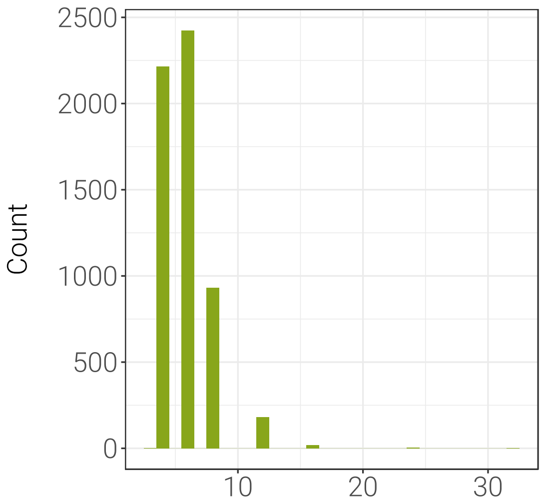



***Figure 7.35*** *Distribution of GPS accuracy*

Figure 7.35 shows a distribution plot of each of the accuracy values for the GPS locations taken into account in this section's results. The values, shown in table 7.9, show that more than 80% of the GPS readings have an estimated accuracy of less or equal to 6 metres and more than 96% of the readings have an estimated accuracy of less or equal to 8 metres.

| Distance | Count | Percent single | Percent cumulative |
|---|---|---|---|
| 2 | 93 | 1.61 | 1.61 |
| 3 | 4427 | 76.66 | 78.27 |
| 4 | 1017 | 17.61 | 95.88 |
| 5 | 180 | 3.12 | 99 |
| 6 | 39 | 0.68 | 99.68 |
| 7 | 9 | 0.16 | 99.84 |
| 8 | 5 | 0.09 | 99.93 |
| 9 | 3 | 0.05 | 99.98 |
| 10 | 1 | 0.02 | 100 |

***Table 7.10*** *Distance between GPS fixes*

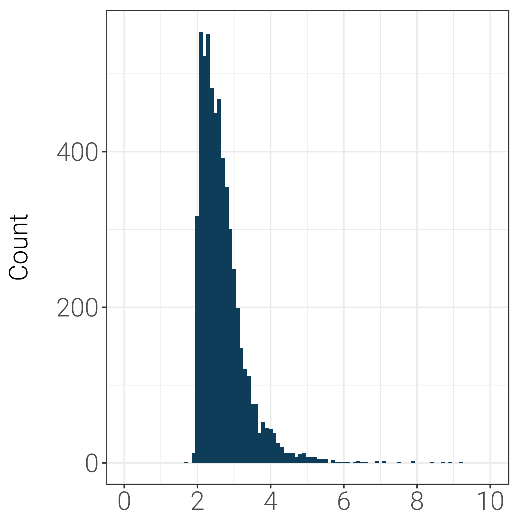



***Figure 7.36*** *Distribution of GPS fixes*

The distances between two consecutive location readings are shown in table 7.10 along with the distribution plot in figure 7.36. While all distances lie under 10 metres, more than

95% of all captured GPS locations are less than four metres away from the previously captured location. The sudden increase around two metres is due to the threshold set in the app to prevent the creation of data at times when no movement is taking place. Both the relative high accuracy along with the coverage of captured locations indicate suitability for solely relying on the device's GPS readings in order to carry out a log analysis. Visual examination of the GPS plots, as shown in figures 7.26 to 7.28 does not reveal any noticeable issues with spatial accuracy, such as rapid locational 'jumps' in random directions.

The map interaction log files were analysed in order to evaluate how the various groups used the app while searching for the treasures. A temporal pattern of interactions reveals no correlation between performance and the amount or distribution of map interactions. Looking at groups that performed generally well but had minor problems at few stages during the run reveals that all except one group showed increased interaction activity during those off-track route segments.

Looking at the percentage of time that the groups had their treasure location in their current map view reveals a positive correlation with performance. While this outcome was expected, there are clear outliers in both directions. Having a treasure in view does not automatically mean that the group will succeed in finding it. At the same time, a group can easily memorise a known location and not use the map while walking towards a treasure. This reveals a general limitation of the approach to solely analyse logs. There is no indication on whether the device was being looked at at a specific time. Analysing the resulting video files showed some occasions where a map view was moved away from all treasure locations and rested there while the group's GPS location persistently moved closer to the treasure location. At a later point in time the map was re-centred on the treasure. It is likely that the group was fully aware of the treasure location but might have accidentally panned the map view while walking and not paying attention.

In order to infer when a map was being used, an attempt was made to analyse whether map interactions increased when the groups moved at a slower speed than average. This could potentially give an indication of when the map was being used and when the group was simply walking. Speed between each captured GPS point was computed using a simple distance through time calculation. In this situation, small GPS location inaccuracies resulted in vastly different speeds between the captured locations. Consequently, the resulting graph showed a lot of noise and was therefore deemed unsuitable for testing such a speculative theory.

Another way to approach the problem of detecting times of no usage could be to additionally log the device's accelerometer readings. This way it can be computed at which times the tablet was being held in an up-facing direction. The times that a device was not looked at could possibly be detected but still leaving uncertainty about the usage when the device is up-facing.

To analyse whether specific map scales were preferred over others, a plot was created per village showing the absolute time that specific map scales were in use. Both villages showed a cluster at 1:1500 - 1:1700, while groups in Matoto preferred small scales and groups in Sembola tended to use large map scales. There are prominent breaks in between the clusters, which can most likely be explained by the way the button zoom functionality is implemented by the used mapping API. No documentation could be found on this topic but testing revealed that the button zoom doubles or halves the current map scale. The minimum and maximum map scales are determined by the tile package's resolution and size and are therefore fixed. Using the zoom buttons when the map is either fully zoomed in or zoomed out triggers specific map scales and most likely causes the observable breaks in figures 7.31a and 7.31b.

During the briefing, the participants were shown two different types of zoom interaction by the research assistant, the two finger pinch interaction as well as a button tap interaction. The buttons were a large tree representing the zoom in functionality and a small tree to zoom out. An observation made during previous field visits was that participants were often hesitant to touch the screen. Therefore, it was expected that few groups would utilise the pinch interaction, which requires longer contact with the touch screen as well as more control. The results do not confirm this expectation, showing that five groups used the button zoom, four groups the pinch zoom and another group used both types of zooms. Possibly, the groups felt less stressed about the touch interactions when they were not observed. No correlation between zoom type and performance or village could be detected, while the data suggest a slight preference of the pinch zoom amongst female groups.

## 7.3 Got it Right Experiment

Working towards building accessible mapping tools (outlined in section 2.4), requires the users to not only understand the base map as a reference, but also the concept of thematic overlays. Using the map as a communication tool that conveys a message in the form of collected data, adds a further cognitive step to the concept of map reading. In the previous experiment, the participants used a map to find several locations marked with a red X. The final experiment carried out for this research aims to answer the question whether data overlays can not only be understood but validated and corrected if necessary. The methodology for this experiment is to have the participants modify the location or the value of a data point. A bespoke Android app, named Got it Right, was created for the purpose of this experiment, which is described in the following section.

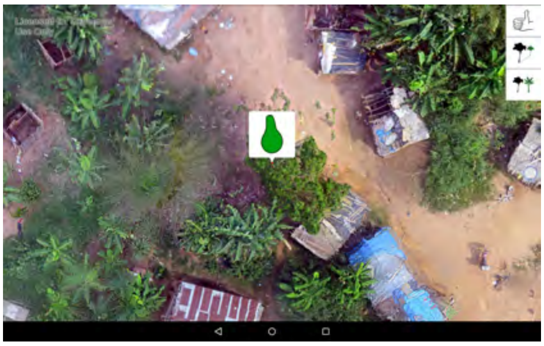
### 7.3.1 Got it Right App

The Got it Right experiment app was developed specifically for this experiment to facilitate the objectives outlined above. As in the previous experiment, the app incorporates a configuration mode for the researcher to configure the initial set-up by pointing to specific configuration files according to the village and test group. The app has been deployed on a Google Nexus 10 device, running Android version 5.1.1. ArcGIS Runtime SDK for Android was used as a mapping framework due to offline capabilities. The app reads in data from a CSV file format exported from Sapelli (see section 2.4.2) or manually created and provides the option to modify the locations and/or the associated features of the records. It consists of four screens shown in Figure 7.37.

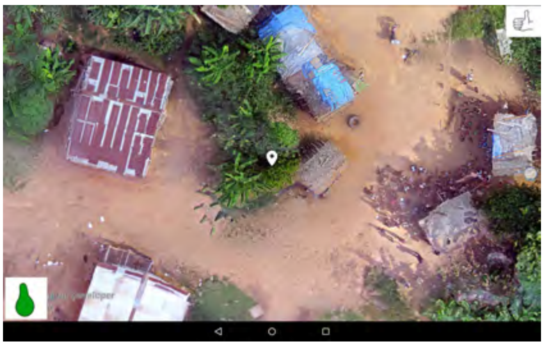
The first screen is for configuration, in which the file paths to the base map tile package, the icon directory as well as the data file and the columns mapping are to be set (figure 7.37a). Previously set paths are remembered to avoid the need to repeat this step for each new participant. Once all paths are set the experiment can be started by tapping the green start button. For each valid record in the provided data file, a location marker showing the associated icon is created. Tapping the triangular shaped 'play' button leaves the administration mode and starts the experiment.

The first screen presented to the participant shows the first marker as an anchor point showing the feature image at the given location (see figure 7.37b). Three buttons in the upper right corner provide the options to either accept the current data point, to change its location or to change the feature. Clicking on the first button showing an 'accept' thumbs up icon proceeds to showing the next marker. Tapping the second button, which illustrates two trees of the same species in different locations, enters the location change mode. In this, the current icon is shown in the lower left corner and a white anchor symbol marks the current location. Tapping at any location on the map updates the current marker location. Once the desired location is marked, the thumbs up icon saves the new location, and exits the location change mode to show the record in its updated position. On tapping the third button, represented as two different tree species, the feature change mode is entered. In this, a white marker showing the feature is shown in the centre of the screen. The results of UI interaction experiments carried out by Vitos et al. (2017) reveal that the participants have higher success and user satisfaction rates with tangible interfaces than navigating through various screens, see section 2.4.3. Building on this experience, a similar approach was chosen for the process of changing a feature at a specific location. By tapping an NFC card at the device, the icon will be swapped for the one shown on the card. Once the desired feature is shown at the specified location, the accept button is to be tapped to leave the feature change mode. When the last record has been processed an alert box is shown, asking the user to discard the changes or save them to a new file.

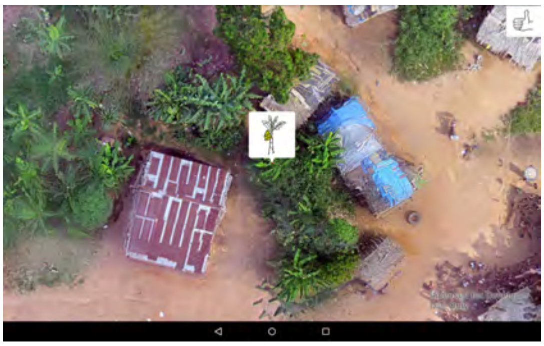

***(a)** Configuration screen*



***(b)** Condition Selection*



***(c)** Location mode*



***(d)** Feature mode*

***Figure 7.37*** *Got it Right app*

## 7.3.2 Experiment Design & Procedure

The experiment was carried out in the villages Matoto and Sembola. In each of them, five resources were identified that match the types banana tree, avocado tree, sacred tree, medicinal tree and palm tree. Like in the Image Tapper experiment, the resources were chosen with the assistance of a local volunteer and were well-known to all residents living in the village. The geographic coordinates and types of all these resources served as a template to derive the set-up constellations for the different modes in different locations. In total, four set-up files were prepared, one for each village/mode combination. Depending on the mode, either the location or the feature in the set-up files were off for four of the resources. In each mode, resource number 3 (medicinal tree) was marked with the correct feature at the correct location.

The experiment was carried out with the same participants who took part in the Treasure Hunt experiment. As opposed to the Image Tapper experiment, see section 7.1, this experiment was targeted at people who have used a map before. After a group returned from the Treasure Hunt, the research assistant showed them all resource locations for the Got it Right experiment in varying orders. Figure 7.39a shows the research assistant presenting the icon used in the software at one of the experiment sites. Following the introduction of resource sites, each participant was separated from the rest of the group, one after the other, and given the briefing for the Got it Right experiment. Depending on the mode, the set tasks were to confirm or correct the locations or features using the Got it Right app running on a 10" screen Google Nexus tablet. For the process of the experiment, the research assistant was sitting next the the participant, either giving the tablet to them or holding it for them, as preferred by the participant. The research assistant obtained his briefing in English, which he passed on to the participant in the local language. The briefing for the Location Correction mode was as follows:

> "You will see images that should mark the locations of the trees we just visited on the map. The images might or might not be at the correct location. If they are not, your task is to tap the 'change location' image *(show icon)* and then tap at the correct location of the tree. The location of the marker will be updated to the position you tapped. You can change the marker position as often as you wish. Once you are satisfied with the position, tap the 'accept' image to move on to the next tree. The experiment will be finished after setting the location of all five trees. You are free to cancel the experiment at any point. Do you wish to continue?"

After giving their consent, the experiment started. The research assistant was briefed to tap the 'location changed' button or the confirm button if the participants tell him to do so. The location changes, however, must be carried out by the participant with no further assistance (see figure 7.39b).

The experiment procedure for the Feature Correction mode was similar to that of Location Correction. The participants could choose to hold the tablet and/or the set of eight NFC feature cards, (see 7.38), themselves or give it to the research assistant. Importantly, they were always given the entire set of cards in a random order from which they had to identify the card with the correct icon and subsequently tap it against the device, as shown in Figure 7.39b.


***Figure 7.38*** *NFC card*

The briefing these candidates received was as follows:

> "You will see images that should mark the locations of the trees we just visited on the map. The images might or might not be correct. If they are not, your task is to find the card with the correct image for the marked tree from the stack of cards and tap the card against the device. The image shown will be updated to the one you can see on the card. This way, you can change the image as often as you wish. Once you are satisfied with the image shown, tap the 'accept' image to move on to the next tree. The experiment will be finished after setting the right image for all five trees. You are free to stop at any point. Do you wish to continue?"

***(a)*** *Demonstration of icons* ***(b)*** *Location correction* ***(c)*** *Feature correction*

***Figure 7.39*** *Experiment procedure*

This experiment was designed to take no longer than ten minutes per person, including the briefing phase, to not discourage participants from taking part. None of the participants seemed under time pressure or rush through the experiment for it to end sooner. In five days the mapping experiment was carried out in two locations, Matoto and Sembola, with 40 participants in each village. Aged between 18 and 61 years old (M=29.03, SD=10.61). The education level between the different villages varies with the distance from a logging town. In Sembola, which is in the direct neighbourhood of Pokola, the 25 out of 40 participants have had formal primary school education and 1 person has attended college for one or two years. In Matoto, 16 out of 40 people have attended primary school.

### 7.3.3 Post Processing

A different configuration file was used per village and per experiment mode to set the initial state of the icons (see figure 7.37b). For this, a CSV file holding the values 'value', 'image_path', 'latitude' and 'longitude' (see listing 7) was read by the app. Each of the experiments output a log file with the same structure but modified values according to the users' choices. For participants taking part in the Location Correction mode experiments, the latitude/longitude values were changed to the location they confirmed on the app and similarly for participants taking part in the Feature mode experiment, the value and image paths were changed accordingly.

**Listing 7** Configuration/log file example

```
value, image_path, latitude, longitude
Banana trees, Banana Tree.png, 1.405395508, 16.32845222
Banana trees, Avocado Tree.png, 1.405534417, 16.32854781
Sacred area, Sacred Area.png, 1.406445185, 16.32812164
Medicinal plants, Medicine.png, 1.405179447, 16.32881625
Palm oil trees, Palm Oil.png, 1.405431363, 16.32900288
```

In the stage of post processing, three tables (results, correct, setup) were added to the database which was previously set up for the Treasure Hunt experiment. Figure 7.40 shows the new tables as well as the existing participants table along with the numbers of entries in each. The table 'results' holds the data extracted from the log files shown above (value → feature, latitude/longitude → the_geom). Additionally, each of the 400 entries links to a participant and holds information on the village in which the experiment took place and the number of the task and the condition, being location or feature mode. The table 'setup' contains 20 entries on the initial set-up (five tasks per experiment mode and village). Similarly, the 'correct' table contains ten entries for the correct location/feature combination (5 tasks per village).

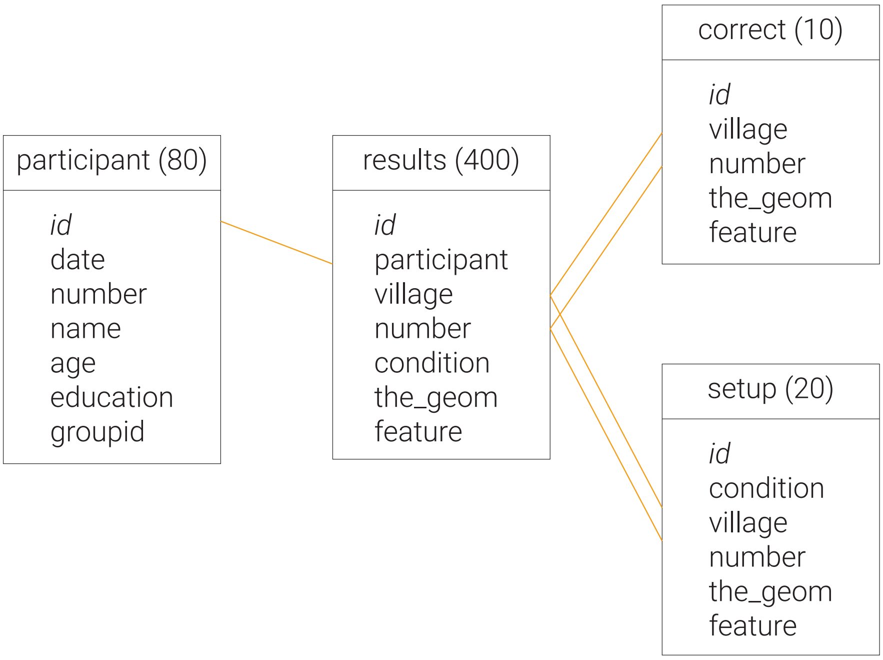



***Figure 7.40*** *Database structure*

**Listing 8** Correct results

```sql
-- Correct Features
SELECT *
FROM results INNER JOIN correct
  ON results.village = correct.village
  AND results.number = correct.number
WHERE condition = 'Feature'
  AND results.feature = correct.feature;

-- Correct Locations
SELECT *
FROM results INNER JOIN correct
  ON results.village = correct.village
  AND results.number = correct.number
WHERE condition = 'Location'
  AND ST_Distance(ST_Transform(results.the_geom, 32633),
  ST_Transform(correct.the_geom, 32633)) < 10;
```

The SQL queries to retrieve correct results from the above database are shown in listing 8. The 'results' table is joined with the 'correct' table, matching the village and task numbers (lines 3-5 and 11-13). For the feature mode, the condition was set to 'Feature' and value in the results table entry must match the value correct table entry (lines 6-7). For location mode, the condition was set to 'Location' (line 14) and the euclidean distance between chosen location in the results table and centre of the sought-for feature is to be smaller than ten metres (lines 15-16). In this experiment, the margin to correct for tap inaccuracies and finger width has been set to to 10 metres, which was previously 100 pixels, geographic reference system. The resulting zones of correct locations in Matoto are shown in figure 7.41.

***Figure 7.41*** *Location buffers*

### 7.3.4 Results

This section presents the results of the Got it Right experiment. First, the overall results are laid out followed by two sections looking into the results of the two modes 'Feature Correction' and 'Location Correction' separately.

Table 7.11 shows the number of tasks that have been completed successfully in total as well as per experiment mode, calculated as shown in the previous section 7.3.3. Out of 400 tasks, 349 (87.25%) were completed successfully. 51 features (12.75%) were incorrectly classified. Regarding the different experiment conditions, 188 out of 200 tasks (94%) in Feature mode were successfully completed as well as 161 out of 200 tasks (80.5%) in Location mode.

**Table 7.11** *Success rate per task*

| Number of Tasks | | Success | | Failure | |
|---|---|---|---|---|---|
| 400 (100%) | | 349 (87.25%) | | 51 (12.75%) | |
| Feature | Location | Feature | Location | Feature | Location |
| 200 (100%) | 200 (100%) | 188 (94%) | 161 (80.5%) | 12 (6%) | 39 (19.5%) |

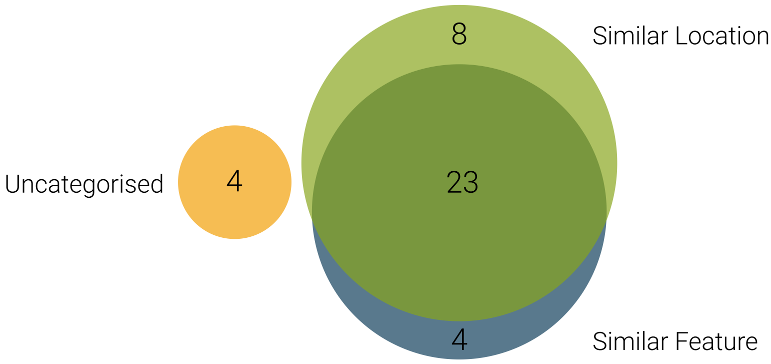



**Figure 7.42** *Error classification – location mode*

The error classification after the approach explained in section 7.1.3 is visualised in figure 7.42. Out of 39 errors made in Location Correction mode, 4 could not be classified. Eight were identified as similar location errors, 4 were similar feature errors and 23 were both similar location and similar feature errors.

**Table 7.12** *Incorrect feature classifications*

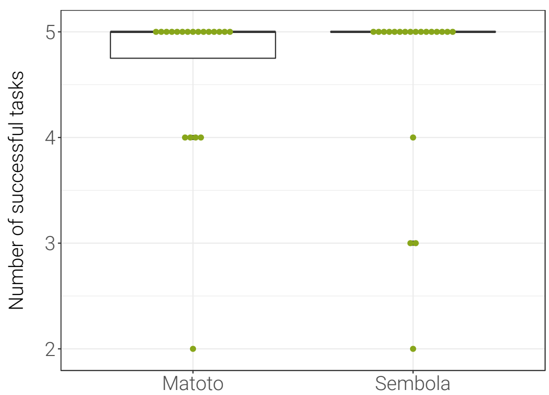
| Village | Chosen feature | Correct feature |
|---|---|---|
| Matoto | Banana tree | Avocado tree |
| | Banana tree | Avocado tree |
| | Sacred area | Avocado tree |
| | Water source | Sacred area |
| | Sweet potatoes | Medicinal tree |
| | Water source | Medicinal tree |
| Sembola | Sweet potatoes | Avocado tree |
| | Medicinal tree | Sacred area |
| | Palm tree | Sacred area |
| | Palm tree | Medicinal tree |
| | Sacred area | Palm tree |
| | Sacred area | Palm tree |

In Feature Correction mode, a total of 12 errors out of 200 tasks were identified, 6 of them in Matoto and 6 in Sembola. The incorrectly classified features are shown in Table 7.12. Four out of 12 times a feature was chosen that was not part of the features introduced in the experiment preparation (see figure 7.39a).

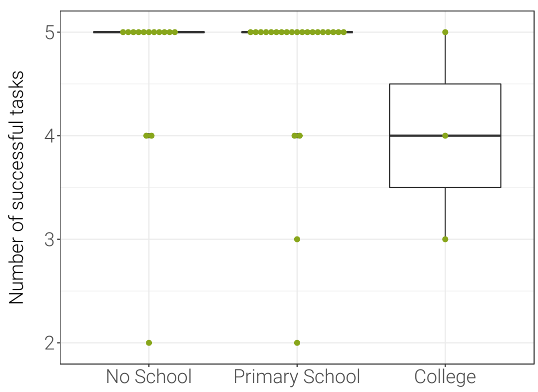
The following section compares the participants' success rates with demographic factors. It presents the results of Feature Correction Mode and Location Correction Mode separately, followed by the combined results. The score rate is the number of tasks a participant scored correctly, with possible outcomes between 0 and 5.

**Feature Correction Mode**

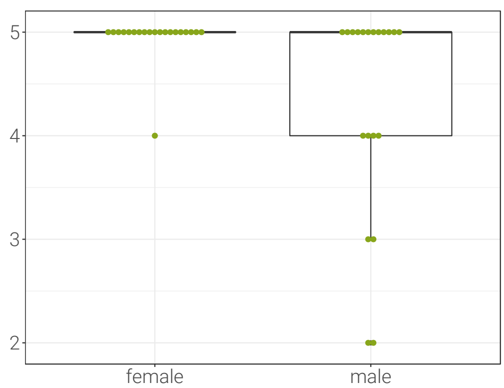
In Feature Correction Mode, the participants' median score rate is 5, with 33 out of 40 participants completing all tasks correctly. Seven participants achieved score rates between 2 and 4 and nobody scored under 2 tasks correctly.




***(a)*** *Village*




***(b)*** *Formal Education*




***(c)*** *Gender*

***Figure 7.43*** *Success rates and demographics*

Figures 7.43a, 7.43b and 7.43c show the distribution of score rates by village, formal education and gender. Both villages have a median score and IQR of 5. Equally, the median score and IQR lie at 5 successfully completed tasks across all education levels including No School, Primary School and College education. The comparison of gender shows that female participants achieved slightly better results in total than male participants. Both groups show a median score of 5. Out of all female participants only one person completed one of the tasks incorrectly while the rest have a score rate of 100%. Male participants achieved a median score of 5 with an IQR of 4 - 5. In this group, 6 participants scored lower than 5.

Figure 7.44 shows the number of successfully completed tasks in regards to the age of the participants. It shows that people who achieved a perfect result of 5 successfully completed tasks have a median age of 25 and a IQR between 22 and 38. For the scores between 2, 3 and 4 the median age increases from 23 to 30 and 36. Given the high success rate of this experiment, the latter numbers are based on very small sample sizes of 2, 1 and 4.

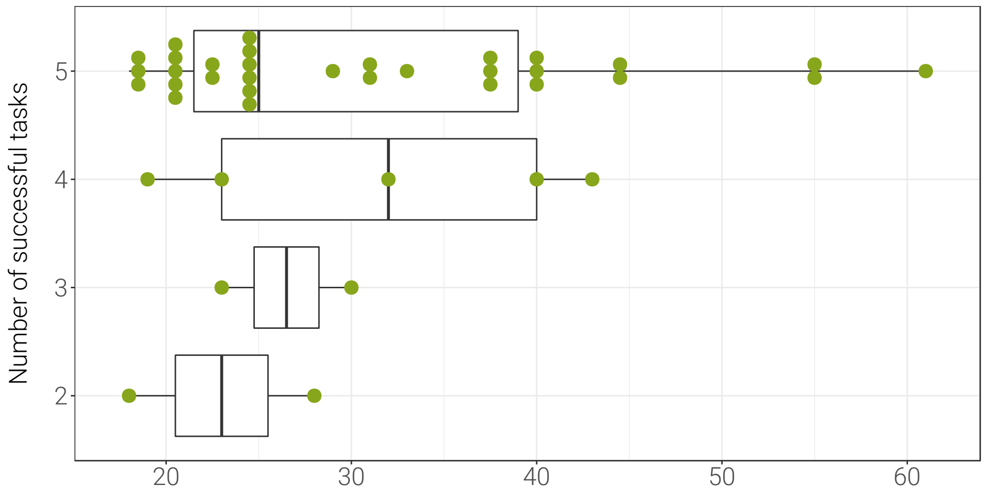
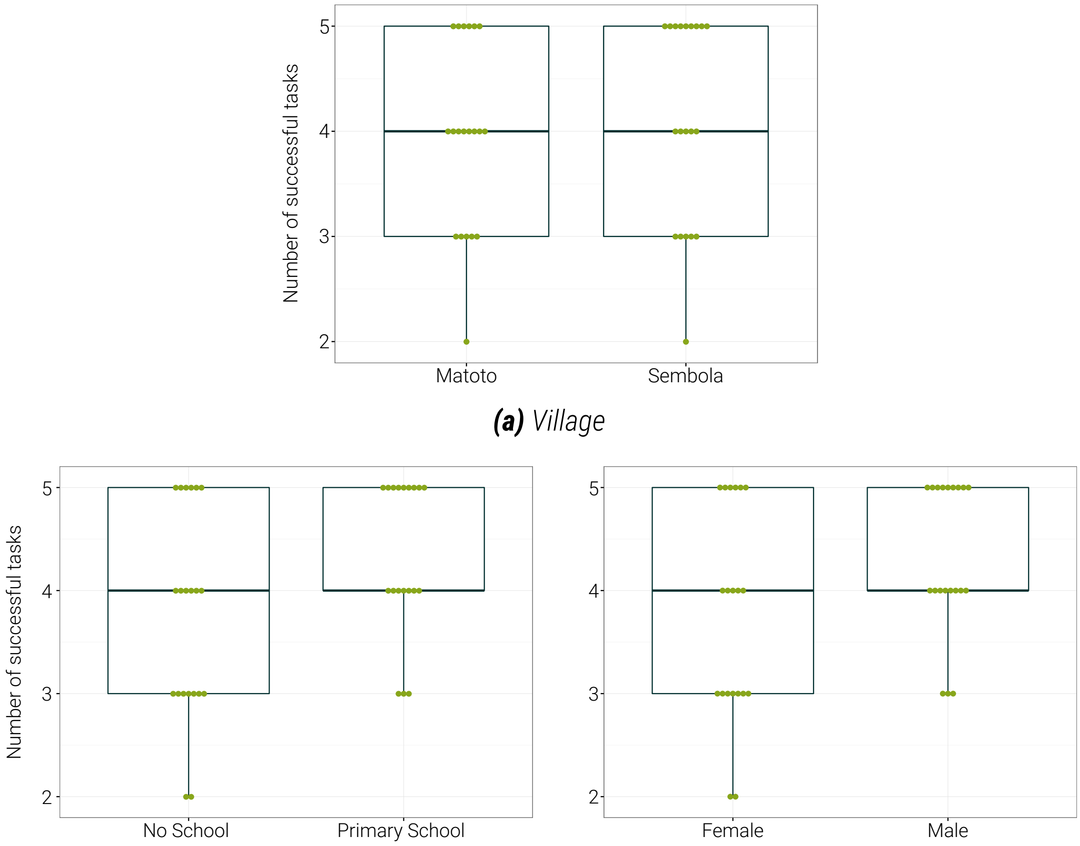



***Figure 7.44*** *Age*

**Location Correction Mode**

In Location Correction Mode, the participants' median score rate is 4 with an IQR between 3 and 5. 15 out of 40 participants completed all tasks correctly. 25 participants achieved score rates between 2 and 4 and nobody scored less than 2 tasks correctly.

Figures 7.45a, 7.45b and 7.45c show the distribution of score rates by village, formal education and gender. Both villages have a median score and IQR of 4 and an IQR between 3 and 5. While the number of participants who scored 2 or 3 tasks correctly are the same across villages, in Matoto 6 people achieved a perfect score, which is slightly worse than in Sembola, where 9 people successfully completed 5 out of 5 tasks. None of the participants attended college. Comparing the results of people who have had formal education at primary school level to those who have never had any formal education shows that both groups have a median score rate of 4. The IQR of participants with no school education lies between 3 and 5 while the IQR of participants who attended primary school lies between 4 and 5 successfully completed tasks. The comparison of success by gender shows a similar pattern as that of formal education. Both groups have a median score rate of 4. The IQR of female participants lies between 3 and 5 while the IQR of male participants lies between 4 and 5 successfully completed tasks.




***(a)*** *Village*

***(b)*** *Formal Education*

***(c)*** *Gender*

***Figure 7.45*** *Success rates and demographics*

Figure 7.46 shows the number of successfully completed tasks in regards to the age of the participants. It shows that people who achieved a perfect result of 5 successfully completed tasks have a median age of 27 and a IQR between 20 and 36. The median age for 4 successful tasks is 19 with with an IQR between 18 and 26. For 3 successful tasks the median lies at 29.5 with with an IQR between 23.5 and 35 and the two people who scored 2 task correctly were 24 and 28 years old.

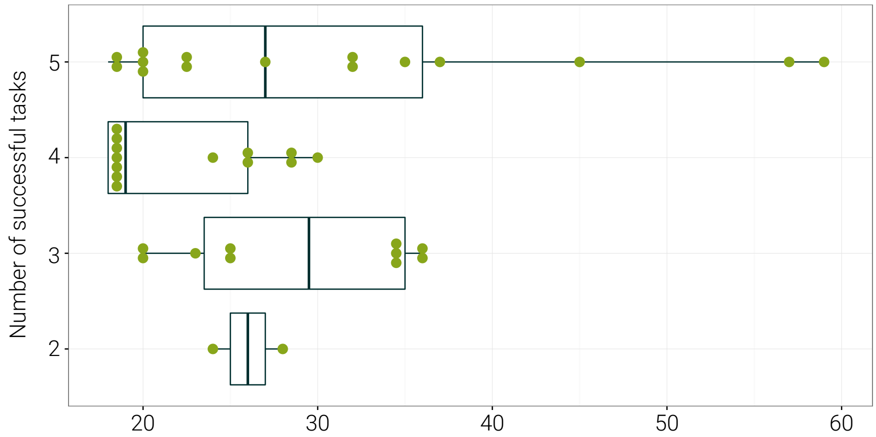
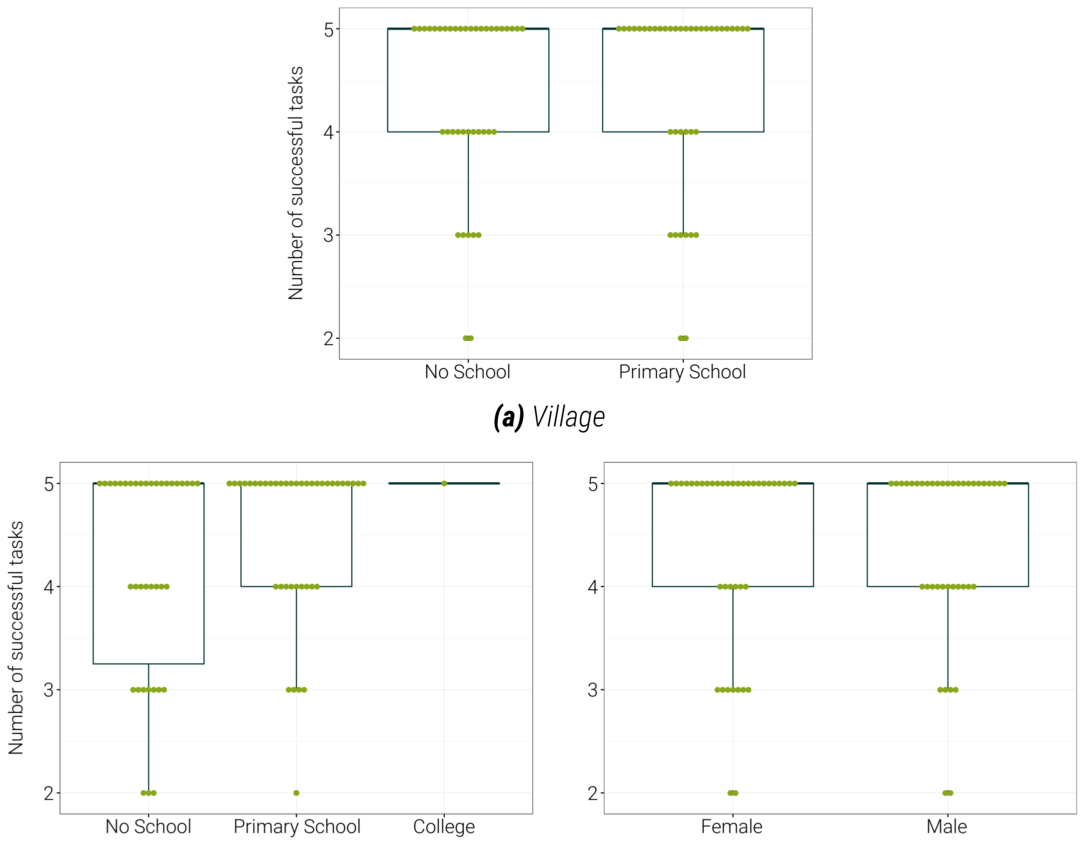



***Figure 7.46*** *Age*

**Location and Feature Correction Results**

Looking at the results of both modes combined, 60% of the participants achieved a perfect score of 5/5 successfully completed tasks. 21.23% achieved a success score of 4/5, 13.75% had a success score of 3/5 and 5% scored two tasks correctly. The overall median is 5 with an IQR between 4 and 5.




***(a)*** *Village*

***(b)*** *Formal Education*

***(c)*** *Gender*

***Figure 7.47*** *Success rates and demographics*

Figures 7.47a, 7.47b and 7.47c show the distribution of score rates by village, formal education and gender. A similar result is shown in both villages, with a median of 5 and an IQR between 4 and 5 correctly scored tasks. When comparing the number of successfully completed tasks by the participants' formal education levels, there is a clear trend indicating that better results were achieved by participants with higher formal education levels. For participants with primary school education, the median lies at 5 with and IQR between 3.25 and 5. Participants who attended primary school achieved a median score of 4 with an IQR between 4 and 5 and one person, who attended college achieved a score of 5. Regarding gender and villages, all groups have a median score rate of 4 with an IQR between 4 and 5.

Figure 7.48 illustrates the number of successfully completed tasks in regard to the age of the participants. It shows that people who achieved a perfect result of 5 successfully completed tasks have a median age of 25 and a IQR between 21 and 38. The median age for 4 successful tasks is 24 with with an IQR between 18 and 29. For 3/5 successful tasks the median lies at 30 with with an IQR between 24 and 35, and for 2/5 the median age is 26 with an IQR between 22.5 and 28.

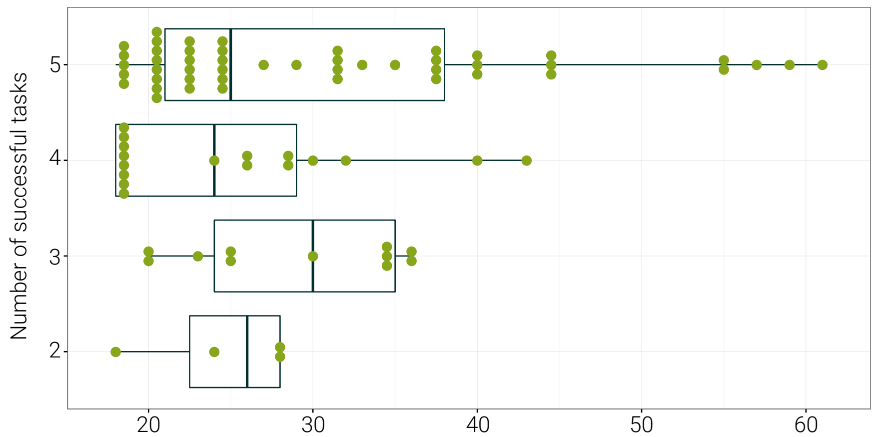



***Figure 7.48*** *Age*

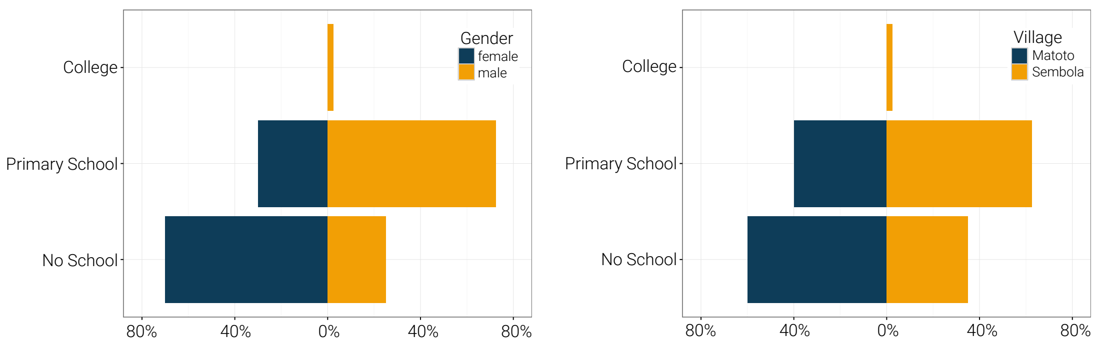
### 7.3.5 Discussion

The high overall success rate of 87.25% shows that most participants understood the tasks and were able to solve the issues. There is some difference in performance of people who were given the task to correct the location of a data point (80.5% success rate) and those who were given the NFC cards to correct the features (94% success rate). This implies that they were perhaps better at recognising specific objects on a map than finding them.

When touching the cards against the device, sometimes the phone did not register the tap because it was too far from the chip reader. In this case the research assistant showed them where to tap it until the change was registered. Participants were quite distressed when this was the case, assuming they did not know what they had done wrong. The very opposite reaction was observable for those participants whose card tap interaction was registered by the device on first attempt. The participants seemed to like seeing how the icon on screen suddenly changed to the one printed on a physical card. The participants' preference of interaction with physical items over touch interaction reflects the findings of Vitos et al. (2017).

Looking at the proportion of women compared to the proportion of men who attended school, as shown in Figure 7.49a, reveals that there is a significant imbalance. 2.5% of male participants attended college and another 72.5% attained some primary school education. In contrast, none of the female participants went to college and 30% attended primary school. The same effect but to a lesser extent can be observed when looking at the level of education by village. Figure 7.49b shows that of all participants in Sembola, 2.5% attended college and 62.5% attended primary school compared to Matoto, where only 40% of the participants attended primary school.

In Location Correction mode, participants with higher formal school education achieved better results on average and male participants performed better than female participants. Interestingly, in feature correction mode, this bias was not apparent in the results. In fact, male participant scored lower than female participants. The level of formal education seemed to not influence the location correction mode results. No distinct difference could be detected between the two villages or any particular age group.




***(a)*** *Education by gender* ***(b)*** *Education by village*

***Figure 7.49*** *Education*

## 7.4 Summary

This chapter addressed Research Question 2: *Are non-literate people able to understand maps and basic GIS interaction?* Over the course of two field visits, three experiments were carried out with two Mbendjele communities in CIB's logging concession in order to evaluate digital map reading as well as basic GIS interaction skills. The overall success rates for each experiment as well as the types of errors or severity of problems occurred are summarised in table 7.13. The initial experiment revealed that the majority of features could be identified on the map with most incorrect identifications being either in a similar location than the sought-for resource or showing a similar feature. As a second experiment, an unsupervised Treasure Hunt was carried out to evaluate understanding of abstract symbology as location marker. All groups returned all four treasures with differences in performance, revealed by the GPS and interaction logs. Finally digital feature and location editing on a bespoke GIS interface was evaluated and showed an overall success rate of 81.43%. Similar to the Image Tapper experiment, most location edits classified as incorrect fall into the categories of similar location, similar feature or both. All experiments showed an overall success rate of more than 80%. The more complex experiments of finding treasures and correcting locations or features on a map showed better results than the basic feature identification. The reasons are most likely due to changes in methodology and prior training. A detailed discussion of the results and the methodology is followed in chapter 8.

***Table 7.13*** *Results overview*

| Experiment | Success rate | Errors / Problems |
|---|---|---|
| Image Tapper | 81.43% | Similar Feature and/or Location 92.31%<br>Unclassified 7.69% |
| Treasure Hunt | 100% | Perfect: 35.71%<br>Minor Problems: 42.86%<br>Major Problems: 21.43% |
| Got it Right | 87.25% | Similar Feature and/or Location 89.74%<br>Unclassified 10.26% |

# 8 Discussion

The research undertaken in this thesis contributes to empowering people living in environmentally sensitive ecosystems whose way of life is severely threatened by social injustice, economic interests as well as climate change. More concretely, the research explored how offline, decentralised and affordable reference maps can be created in the Congo Basin using UAVs, and whether people without prior map knowledge can understand maps and basic GIS interaction in order to eventually gain ownership of mapping processes and become stakeholders in environmental efforts affecting their livelihoods.

This chapter summarises and discusses the findings and contributions of this thesis, as well as the applied methodology and the required modifications thereof, imposed by the context of the rainforest setting. The research impact is demonstrated, followed by a review of further work to be undertaken in order to realise the vision that motivates this research.

## 8.1 Addressing the Research Questions

The "power of maps" (Wood, 1992; Harris and Hazen, 2005) as well as the potential of PGIS to give communities a voice (Pánek, 2016) have been widely accepted in the literature (see section 1.2.4). In the development context, however, authors are divided over the question as to what kind of technology has the potential to empower or disempower (Chambers, 2006; Corbett and Keller, 2005). No literature has been identified to have carried out systematic tests on whether maps and GIS can be used and understood and therefore controlled by marginalised people with no map-using culture. This thesis addresses the overall Research Question: *Do non-literate hunter-gatherers in the Congo Basin understand digital maps?* The main contribution of this research is to show that if GIS technology is developed with people in mind, it can be understood even by non-literate forest communities. In other words, if enough context is presented on the map conveyed in a photo-realistic rather than textual way, using GIS in development work does not inevitably mean 'putting technology before people' (see section 2.5).

In approaching this challenge, it became evident that in order to make digital mapping tools usable for a wider population, usable digital maps are required as a first step. Thus, the first Research Question was defined as: *How can appropriate base maps be created?*. Appropriate, in this case, refers to the given context of the rainforest and its inhabitants. A feasibility evaluation of offline, decentralised and affordable map creation using UAVs was carried out with the objective to design a reproducible methodology that allows researchers as well as people working in the humanitarian sector to create maps that are usable by local populations.

With the results of that objective in mind, the second Research Question was defined as: *Are non-literate people able to understand digital maps and basic GIS interaction?* This question was approached by designing three experiments around basic aspects of GIS functionality in order to test the understanding of a digital base map, the understanding of abstract symbology as location markers, and the performance of editing marked locations or features on a digital map. The following parts of this section will summarise the key findings of each Research Question followed by a general discussion of both topics of map generation and map understanding.

### 8.1.1 RQ1 – Findings

Literature shows that UAVs have been utilised to map various landscapes, including temperate forest (Dandois et al., 2015) and rainforest areas (Zhang et al., 2016; Perroy et al., 2017). For this thesis, the special focus of UAV-borne image acquisition and map creation was on restrictions on time, internet access, Ground Control Points (GCPs), processing power and costs. In order to answer RQ1, different cameras, flight parameters, georeferencing methods and processing software were tested. The results were evaluated for quality and feasibility in relation to creating appropriate base map imagery for the described context.

Summary of findings:

- Camera with wide angle and fast shutter speed is suitable
- 90% endlap for image alignment
  80% endlap for scene reconstruction is appropriate
- Use of GCPs where possible
- Use of proprietary software for SfM at present stage

The proposed solution is to increase endlap through photo interval while, if necessary, reducing sidelap. Due to low distinct texture in forest canopy, high endlap during image alignment is important for scene reconstruction. Redundancy can be reduced for scene reconstruction processes. Trials of alternate cameras show that a wide-angle action camera is most suitable for this task. The fish-eye lens is of advantage due to its wide angle and the resulting image overlap. The barrel distortion does not show in the final product, processed with Agisoft PhotoScan (see section 6.3.4). The camera's weight does not influence the flight time (see section 6.3.1), while the photo trigger interval is of higher importance as it allows for increased forward overlap at higher speeds.

A considerable limitation when carrying out Structure from Motion (SfM) processing on a portable computer was the restricted processing power and the resulting time requirement. In order to significantly decrease processing time, while achieving good results, a 90% endlap was proposed for stage of image alignment, which was reduced to 80% for the resource-heavy process of scene reconstruction. Indirect georeferencing methods generated more accurate results than directly reading location information from geotagged images. Poorly distributed GCPs showed sufficient results if high accuracy in camera alignment was achieved. It is suggested to use GCPs where possible and if not, many smaller flights with varying pattern directions are recommended to minimise systematic errors.

### 8.1.2 Contributions to Map Generation

This research demonstrates that it is possible to create high resolution maps of areas which are currently insufficiently mapped, which have the potential to be used in participatory mapping projects with indigenous communities. As shown, this can be done on site using relatively low-cost equipment.

UAV-borne aerial mapping techniques can produce high resolution, georeferenced aerial maps of the Congo rainforest, which exceed the quality of all available products. The non-commercial satellite Sentinel 2, in comparison, achieves a ground resolution of 10 metres at which single features are not distinguishable (see section 2.3.2). The orthophotos produced in this research show a spatial ground resolution of 10cm and successful reconstruction of distinct shapes, such as tree canopy and huts (see section 6.3.5).

The required UAV, camera and software can be purchased 'off the shelf' – no customisation is required. Thus, the systematic process proposed in this research can presumably be used by non-experts to transfer mapping techniques to similar challenging environments. The technical expertise required to carry out the full mapping process as proposed in this thesis (see section 6.5) includes learning basic piloting of the quadcopter for landing and emergency situations. All used software have graphical user interfaces and should be configurable by a person with basic computer skills.

Equipment to produce high resolution maps is likely to be affordable by non-profit organisations, at a total cost of less than £4500 (see section 6.5). As opposed to purchasing a final product, the majority of costs when creating maps using a low-cost UAV are a one-time expense. Operational costs are generally low (see section 3.1.1) but are dependant on local logistics (i.e. accessibility of area to be mapped), salaries as well as potential costs of official flight permits (see section 8.1.3).

Challenges to be overcome relate both to access to a suitable power supply for the laptop and to legal and other related issues involved with obtaining permits to fly UAVs. While it is possible to bring several fully charged batteries to the field in order to power the UAV and camera, image processing is a resource heavy operation and requires an in-situ power supply. Flight permits, again, are dependant on external factors that cannot be controlled.

### 8.1.3 Discussion on Map Generation

This research has shown that orthophoto map creation using UAVs allows to capture areas at a very high resolution, and to create local maps of previously unmapped territories. However, the UAV-borne aerial mapping approach does not come without limitations. Some of them have been discussed as part of the Research Question while others cannot be overcome through design solutions. It has to be acknowledged that it is currently not possible to use UAVs for the purpose of producing detailed maps of extensive areas as scaling up is restricted by several factors. With the proposed method, four batteries and 25 hours of processing time were required to map an area of 600x600m. If the area needs to be scaled up, more storage capacity, power and time are required and, importantly, more forest clearings are required to start and land the aircraft. For an experienced pilot, it is possible to navigate a multi-rotor UAV through little clearings in canopy but it still requires a lot of little clearings due to the limited reach. Depending on local geography, it might be possible to occasionally get enough open space to manoeuvre a fixed-wing aircraft above the canopy but it is unlikely for that to be an option across a large area of rainforest.

Flying unmanned aircrafts above forest canopy comes with more limitations, as in some countries, including the UK, it is restricted by law to lose the UAV out of sight at any point during the flight process. This restriction posed challenges to testing the equipment and flight set-ups before leaving to the field, as discussed in section 6.2.2. There is an ongoing argument about safety and privacy versus innovation (van Wegen and Stumpf, 2016). As shown in the literature review, section 3.1.1, with the exception of Gabon, the countries situated in the Congo Basin do not have any official legal framework in place regarding the use of civilian UAVs (see figure 3.3). The lack of formal regulations in the Republic of the Congo might be perceived as convenient, but in fact makes the situation more complex, as the country's local authorities make unilateral decisions on a case-by-case basis, typically for their own benefit.

During the visa application processes in preparation for both research trips in which a UAV was brought into the country, a list of equipment was presented to the Honorary Consulate Of The Congo Brazzaville in London, where it was signed off without any complications. On arrival at the international airport in Brazzaville in January 2015, a local employee of the logging company CIB proposed to handle the luggage whilst still at the airport to not attract unwanted attention. The same tactic was applied for all internal flights, and on arrival at CIB's headquarters in Pokola, the staff confirmed that flying the UAV would not cause any problems as long as it is within the bounds of the company's logging concession. The flights were carried out accordingly and without interruption.

The subsequent research trip to Pokola in December 2015, however, did not go as smoothly. On arrival in Pokola, CIB staff explained that in order to fly the UAV, they must first apply to the local authorities for permission. This caused uncertainty and a delay in carrying out research. One week following the arrival, the company claimed that the application had been successful and the first flights to produce the orthophoto maps could be carried out. However, following the initial UAV flights, the local police arrested the researcher, confiscated the UAV as well as the researcher's passport claiming that the UAV was flown whilst the application was still pending. This issue was eventually resolved by CIB staff through negotiations and the payment of a fee to obtain the passport, the UAV as well as the official flight permission.

In a conversation with the documentary team of the French-German TV channel ARTE in Pokola (December 2015), the film-makers confirmed that based on their own experience, it is becoming more and more difficult and expensive for them to obtain permission to use an UAVs for filming, since local authorities are increasingly taking advantage of the situation for their own financial benefits. The unpredictability of how individual officials choose to handle UAV flights indicates an uncertain future for the feasibility of using UAVs as research tools in the Republic of the Congo and similar unregulated areas.

As an alternative to the more expensive proprietary software model, the open-source processing tool chain OpenDroneMap was tested. While smaller datasets (~100 photographs) could be successfully aligned if enough overlap was given, the software repeatedly ran into different issues when processing larger datasets of flights taken in Matoto or Sembola (see section 6.3.4). Apart from processing requirements, software bugs were encountered repeatedly. However, despite problems with the current state of the software, the project is well maintained and contributors are responsive to bug reports while constantly working on solutions for current problems as well as improving parts of the algorithms according to current state-of-the-art technology. Since there is no direct revenue or profit from selling the software, it is a general limitation of open-source projects to evolve strictly according to the needs and the agenda of their developers. The reliance on open-source technologies creates a strong dependency on the developers or community of the software, not only in terms of roadmap and feature requests but also for the fixing of software bugs and providing documentation. With gained understanding of the SfM through carrying out this research, it has been possible to work around some of the current issues. For people with no interest in technology and work-around solutions, an out-of-the-box solution (e.g. Agisoft PhotoScan) is recommended. OpenDroneMap is to date too premature to rely on, but shows potential for the future.

This is not to say that there are no problems with proprietary software. During this research, an important factor of uncertainty was the GroundStation iPad app by DJI, 2017b, which was used to upload waypoints to the UAV to initiate the automatic flight execution. Supposedly after an automatic update, a bug was introduced that caused the app to exit at random points during the flight pattern set-up. While in the field, there was no chance to find an alternative solution to uploading waypoints to the UAV, which almost caused the cancellation of aerial image acquisition, which would have influenced all planned experiments. Repeated attempts revealed that approximately one in seven times the app would not close before the waypoints were uploaded to the UAV.

### 8.1.4 RQ2 – Findings

Research question 2: *Are non-literate people able to understand digital maps and basic GIS interaction?*, set out to investigate whether digital maps, if detailed enough to differentiate dominant visible features (e.g. trees, huts), are understood as representations of a known landscape. This question was further subdivided into two parts. RQ 2a: *Are non-literate hunter-gatherers able read maps?* aimed to test whether the produced aerial orthophotos are understood as a representation of a well-known geographical landscape, even if participants had never seen the landscape from that angle. A feature recognition experiment was carried out to evaluate readability of a basic photographic reference map and an immersive Treasure Hunt experiment was carried out to evaluate understanding of abstract symbology as location marker. Finally, RQ 2b: *Are non-literate hunter-gatherers able contribute to maps?* was addressed by evaluating digital feature and location editing performance on a bespoke GIS interface. The findings of each of these tests are summarised in the following paragraphs.

Obj 1: *Evaluation of base map understanding in relation to own location and environment*
The experimental approach to address this objective was to test whether people can find familiar locations on a digital, aerial orthophoto presented on a tablet. Each participant was asked to locate four known forest resources as well as their own location on the digital map. Half of the participants were presented with rotating images, in order to find out whether there was a preferred way of aligning the image in relation to the environment.

Summary of findings:

- Success rate: 81.43% correctly classified tasks
- Map rotation showed no effect
- 92.31% of errors not random
- Correlation between success rate and education
- Age had no influence on results

The experiment revealed that 81.43% of the tasks were completed successfully. A total of 7.69% of all errors appeared random, suggesting that with more training and less pressure the tasks could be completed successfully. During the execution of this experiment, the log files of 12 participants were excluded from evaluation due to interruptions during the experiment process, which is further discussed in section 8.2.1. The findings of this experiment led to the conclusion that most people could instantly and without any training understand the relationship of features shown on the map with the real environment, which made it possible to focus the next test on map symbology.

Obj 2: *Evaluation of understanding abstract symbology as location marker*
The typical representation of thematic content in cartography and GIS is to overlay a reference map with abstract symbology, representing information. To test the understanding of this concept, a Treasure Hunt experiment was designed, in which groups of four participants had to navigate to four treasure locations marked with a red cross on a digital map. The symbol was intentionally chosen as an abstract symbol explained to participants to mark locations. The focus here was explicitly on understanding the concept of symbols being used as markers as opposed to answering the questions as to what symbology is appropriate, which is subject to further research (see section 8.3).

Summary of findings:

- Success rate: 100%
- Most groups took shortest route
- GPS accuracy adequate for log analysis
- No preference of scale identified
- No preference of zoom type identified

A total of 80 participants took part in the Treasure Hunt experiment. Due to prohibited team building across groups and GPS and software failure, discussed in section 7.2.4, the resulting sample was decimated to 14 valid runs, which does not allow for drawing generalised conclusions. Nevertheless, all participating groups returned all treasures, which gives a strong indication that the marker locations could be understood. To further discuss the results and to identify problems encountered, four measures of success were defined and used for analysis: routing strategy, relative route length, length of detours and number of detours. Looking into difference of performance revealed that five groups returned all treasures without experiencing problems, six groups experienced minor problems and three groups experienced more severe issues in attempting to find the treasures. The log analysis has not revealed any preference in terms of preferred map scale of zoom type. The overall results showing that the treasures could be found, made the third experiment possible, in which marker position or features were to be modified.

Obj 3: *Evaluation of performing location and feature editing in GIS*
The final experiment aimed to answer the question whether thematic data overlays can not only be understood but validated and corrected if necessary. The methodology for this experiment was to ask the participants to modify the location on the digital map or the icon representing the value if it does not match the reality.

Summary of findings:

- Success rate: 87.25% correctly edited tasks
- Feature correction success rate (94%)
  higher than location correction success rate (80.5%)
- 89.74% of location editing errors not random
- Slight trend towards better success rates with higher education levels
- Age had no influence on results

The high overall success rate of 87.25% shows that most participants understood the tasks and were able to solve the issues. There is some difference in performance of people who were given the task to correct the location of a data point (80.5% success rate) and those who were given the NFC cards to correct the features (94% success rate). This implies that they were perhaps better at recognising specific objects on a map than finding them. Apart from performance, the participants seemed to like seeing how the icon on screen suddenly changed to the one printed on a physical card and generally seemed to prefer the haptic over digital interaction. In location correction mode, 89.74% of all location errors where defined as similar location. This again indicates that participants did not tap on random locations and with more training and less pressure the tasks could potentially be completed successfully. Similar to the Image Tapper experiment, people with higher education achieved generally better results, while the participants' age did not show an effect on the results.

### 8.1.5 Contributions to Map Understanding & Interaction

This research demonstrates that indigenous, non-literate people can understand aerial maps of their environment, without prior training. Despite not being familiar with modern devices such as tablets, they can interact with digital maps on these devices. Prior to this research only anecdotal evidence existed (see section 2.5), but no systematic study had been carried out on the use of maps by marginalised communities that do not have a mapping culture.

The maps created by the UAV mapping process developed in this thesis are sufficient for the purpose of mapping the forest environment in the Congo to a level of detail where the indigenous inhabitants on the map can locate individual features of importance to them – e.g. trees, food supplies.

Map alignment is not required for reading aerial photographic maps of familiar space. Only one participant physically aligned the map with the surrounding environment and no difference in success rates was shown between people who had a static and those who had a rotating map view and needed to adjust to a different viewing perspective for each task (see section 7.1.4).

Indigenous, non-literate people can understand the meaning of a thematic location marker overlaid on a reference map. Success rates of 94% for feature editing and 80.5% for location editing show that the tasks were understood as well as the concept of thematic map overlays on a specific location.

There is an educational bias with better results being achieved by people with higher levels of formal education. This was both apparent in gender difference, with more male participants being formally educated, as well as per village, with higher education levels in Sembola (see section 7.1.5). Age showed no influence on map reading skills across the different experiments (see sections 7.1.4 and 7.3.4).

Indigenous, non-literate people can pan/zoom to navigate to locations marked with an abstract symbol. A brief demonstration proved to be sufficient for people to be able to successfully operate pan/zoom functions in an unsupervised scenario. Despite the small sample size it can be said with fair confidence that people were able to use map interaction controls and gestures to solve the task of navigation.

Indigenous, non-literate people can edit and correct map marker locations and features on a digital map. Locations were successfully changed by participants through direct tap interactions and feature icons were updated by tapping according NFC cards.

### 8.1.6 Discussion on Map Understanding & Interaction

Despite the high visual realism, reading an orthophoto map is a demanding cognitive task. An orthophoto is a snapshot in time, whereas the experienced reality is undergoing constant change. People look horizontally out across the environment from a vantage point that is close to the ground. Using a map requires to mentally 'translate' from the constantly-changing, horizontally-viewed world into a static, vertically-viewed map (Kastens et al., 2001).

Presson (1982) claims that reading a map requires the reader to understand the correspondences between the map and the space that it describes (see section 3.2). Two types of correspondences are distinguished, with this research experiment results showing that both identity correspondence (Image Tapper experiment) as well as relational correspondence (Treasure Hunt experiment) could be understood.

Numerous studies have been carried out regarding 'world-to-map' as well as 'map-to-world' problems, often in combination. The first require the reader to identify a real-word feature on a map, e.g. self-localisation (Levine, 1982; Klippel et al., 2006), the latter requires to translate features shown on the map into the real world. In way-finding and navigation tasks, both problems have to be solved as the map reader first identifies their own location on a map before finding a suitable route to a destination that can be followed in the real world (Allen, 1999). In solving a wayfinding task, the map is typically used as a means of orientation in an unfamiliar or semi-familiar environment. In this research, experiments were carried out addressing both concepts, 'world-to-map' and 'map-to-world'. There is a fundamental difference, however, as it was not the environment and spatial knowledge that is new to people but the representation thereof. When it comes to spatial knowledge acquisition of an environment, authors such as Darken and Peterson (2001) make a distinction as to whether the knowledge is acquired through direct exposure to an environment or from a secondary source, such as a map. This study incorporated people who have learnt the environment strictly through direct exposure. The knowledge of the environment, however greatly exceeds that of an average western, urban citizen (Lewis, 2002).

Map reading studies with children, whose spatial knowledge as well as cognitive skills are still developing, revealed that correspondences with a map and the environment could be established if the map was physically aligned with the environment (Liben and Downs, 1993; Blades and Spencer, 1990). The findings of this research show that none, except for one of the participants aligned the tablet with the environment when they were asked to find features around them. Interestingly, participants that were prompted not just with unaligned but rotating map views scored insignificantly better than those with static map views. A potential explanation as to why map alignment was not necessary is that a world-to-map problem was posed to people who have a vast knowledge of the immediate world and therefore a photographic map of familiar space is sufficient to carry out the required mental transformation (Aretz and Wickens, 1992). This confirms the findings of Nori et al. (2006) that people with survey (or configuration) knowledge do not show an alignment effect (see section 3.2.3)

Formal education showed a positive correlation in both experiments carried out by one participant at a time: Image Tapper and Got it Right (Feature Correction mode could not be analysed, due to high success rate of 94%). Medhi et al. (2010) investigated the correlation between literacy and cognitive skills for conceptual abstraction and concluded that non-literate users have different cognitive skills for abstraction, in comparison with literate populations. She states that "[n]on-literate people have been shown to learn poorly from neutral, stand-alone objects (such as a book, or automated system) which contain a set of instructions to be applied across situations (...). Rather, they tend to learn better in situ, embedded in concrete situations and practical experience" (Medhi et al., 2010: p.3). The Treasure Hunt experiment, which was designed as a participatory and embedded learning experience could explain the high results of the subsequent Got it Right experiments compared to the Image Tapper experiment, which was deliberately carried out without prior training.

The group assigned to carry out location correction during the Got it Right experiment had a success rate of 80.5% while the group carrying out feature correction using the NFC card achieved a success rate of 94%. The fact that the feature detection group achieved higher results is remarkable, as both groups need to identify the marked locations on the map, while the feature correction group additionally had to identify the correct icon. It is possible that the group carrying out location correction did not understand the instruction to identify a specific, previously visited location and thus chose any resource matching the shown icon. However, as shown in chapter 7, most errors were systematic, implying some understanding. The error classification showed that out of 39 incorrectly edited locations, eight were identified as similar location errors, four were similar feature errors and 23 were both similar location and similar feature. It has to be noted that some level of error is to be expected as mismatching reality with visually similar map locations occurs in Western populations too, shown in Davies and Peebles (2010). Feature identification could have been successfully completed without a specific reference point if the marked resource was identified and assigned to the right icon on the NFC cards.

While the resource icons, adapted from existing Sapelli projects, see (Vitos et al., 2017), seemed to be clear to the participants, they had more difficulties understanding navigation buttons to enter and leave specific modes in the Got it Right App. These icons, shown in figure 8.1, were more abstract and therefore it was decided to allow the research assistant to help in finding the correct icon in order to be able to test the feature/location editing objectives.

***(a)*** *Location Editing* ***(b)*** *Feature Editing*

***Figure 8.1*** *Got it Right editing modes*

The zoom buttons of the Treasure Hunt app (small tree = zoom out, large tree = zoom in) were seemingly better understood, as they were frequently used (see section 7.2.4). The interaction logs revealed that the zoom buttons and two-finger pinch-zoom gesture were used to a nearly equal amount (see section 7.2.5). During the supervised experiments people appeared cautious, sometimes intimidated when prompted to interact with the touch screen. People were seemingly more confident in exploring the touch screen interaction when they were amongst themselves. In general, there was no clear pattern of the way participants interacted with the device during the Treasure Hunt, as shown in figure 7.29. Some groups showed high frequencies of interaction, while others showed little device usage activity. No correlation between interaction frequency and success levels of completing the tasks could be detected.

While there is research that indicates that mapping is a cultural universal (Blaut et al., 2003), this research provides further evidence that photorealistic maps could be understood and used without much prior training. Map symbology and iconography, however, is strongly dependant on culture and requires further research. By stating that maps were understood by the experiment participants does not imply that every user is an expert. Even in cultures accustomed to map-reading, vast differences exist between individual performances of reading maps. Kastens et al. (2001) argued that skilled map use is not an ability that develops naturally, like walking or talking. Instead, it is a complex ability that needs to be taught and practised if it is to be fully developed.

### 8.1.7 Contributions to Usability Research 'in the Wild'

This research demonstrates that a number of existing techniques from usability engineering – in particular activity logging and participant observation – can be transferred from the lab to enable research with non-literate, indigenous communities, overcoming cultural and linguistic barriers. The research outcomes make way for further inclusion of indigenous non-literate people in mapping research.

With appropriate local assistance including on-site translators and using a FPIC approach, it is possible to recruit sufficient participants to be able to draw preliminary conclusions about the effectiveness of computer logging techniques. Other techniques, such as 'Think Aloud' are not able to be successfully transferred into this context (see 7.1.2).

During the supervised experiments participants had to be prompted several times by the research assistant to interact with the touch screen and were seemingly uncomfortable with it. The interaction logs show a high number of pan and zoom interactions when they were not under direct observation (see section 7.2.4). This strongly suggests that the participants may have felt socially inhibited in front of a Western researcher watching them use novel and (as far as they knew) expensive and fragile equipment. A recommendation derived from this finding is for future field workers who carry out research with similarly marginalised groups interacting with digital devices to "let them go off and play".

Interaction logging methods proved sufficient to analyse map usability through the measure of error rates across language and cultural barriers. Furthermore, interaction logging methods paired with GPS location readings proved sufficient to analyse map use behaviour across language barriers in an unsupervised wayfinding exercise. Creating video files of map interactions over time and space provides a useful tool to carry out this type of log analysis. The GPS accuracy is adequate for this type of log analysis, however, inferring when a map is in active use remains a challenge (see section 7.2.5).

Within the groups studied, there is a collective approach to problem solving. During the Image Tapper experiment participants often sought help from bystanders or research assistants and it was difficult to enforce a single user test environment. When these dynamics were considered in the experiment design of the Treasure Hunt, a success rate of 100% was achieved (see 7.2.4).

## 8.2 Context Related Considerations

This section discusses experiences of working with indigenous, non-literate communities in the rainforest, including methodological barriers and approaches to overcome these. Finally, the constraints imposed by institutional collaboration in the given context are highlighted as well as the challenges and opportunities encountered when working in an interdisciplinary setting.

### 8.2.1 Research 'in the Wild'

Usability experiments, as they are defined in the HCI literature, come with a strict set of rules and guidelines. Carrying out structured experiments in the rainforest introduces significant challenges, such as cultural differences, communication barriers as well as time constraints, which make it difficult to follow traditional HCI test protocols. The challenges imposed by the context of this research and the according adjustments to carry out this research are discussed in this section.

The core method of User-Centred Design (UCD) is the iterative design cycle (see 4.1), consisting of the phases: observation, idea generation, prototyping and testing. This research was informed by anthropologist, Dr. Jerome Lewis, who gave extensive briefings to the research team about the lifestyle of the pygmy hunter-gatherers as well as their problems and needs. Nonetheless, a scoping field trip was carried out without immediate research plans, matching the observation phase of the UCD cycle. Given the setting with the unknown environment and culture for the researcher, this phase turned out to be essential for the understanding of the context, which could not be delivered through expert briefings. Idea generation and quick prototyping were applied for all experiment apps, with the first one being developed in the field, responding to given circumstances.

A key issue during all supervised, empirical experiments was the local people's discomfort at being evaluated on a one-on-one basis. Most of the participants have not attended formal education and have never before been in an artificially created stress situation in which they were told to solve a problem without being allowed to collaborate. Pygmy hunter-gatherers are used to a communal way of life, so participants were not at ease with undergoing individual tests. This resulted in consistent interruptions from bystanders and translators jumping in with hints when a participant struggled with a task. Instructing them not to interfere seemed to be taken as an offence. As an outcome, some results of the Image Tapper tests were skewed and had to be removed from the evaluation.

Semi-structured interviews as well as the Thinking Aloud method, both being common empirical research methods in usability engineering, were initially attempted, but discarded after it became clear that they would not be fruitful but instead increase the stress level of participants. For instance, when participants were asked follow-up questions on tasks they evidently struggled with, they consistently said that everything was clear to them and they were happy with the given task. Often it seemed like people gave the answer they expected the researchers would like to hear. With Thinking Aloud, participants were too nervous and lacked contextual understanding to describe their actions. This was further complicated by the problem of multiple language barriers.

Translators played a crucial role in this research, making sure the meaning of a sentence is not lost or changed during multiple translations. Depending on the complexity of the context, sometimes it was necessary to translate from English to French to Lingala to Mbendjele. For this, the translator was given written briefings in English, (see 7.1.2, 7.2.2 and 7.3.2). As opposed to usual procedures, the instructions could not be given in a standardised way, given the lack of written language in Mbendjele. Instead, much time was spent with the English speaking research assistants to make sure he fully understood the purpose and procedure of the project. Having gone to university himself was of great advantage as he was able to relate to the context and procedure of academic research. It needs to be pointed out that having met a university educated, fluent English speaker in the small logging town of Pokola was a lucky and unforeseen coincidence.

However, regardless of understanding the language, the issue of non existent vocabulary and context remained a challenge. Some of the concepts could be translated into simplistic language. To 'zoom in', for instance, became 'make trees bigger', as this was also the symbol used for the button. More complex ideas were left to the research assistants to deliver in lengthy explanations. At no point was it possible for the researchers to intervene, due to their lack of understanding the ongoing conversation.

### 8.2.2 Adaptations of Methodology to Local Context

During the pilot study, detailed in section 7.1, it became clear that a simple experiment was required where understanding could be measured through successful and unsuccessful task completion. This resulted in the design of the Image Tapper experiment, based on a simple app, which logs user interaction. All experiments were carried out in one of the public huts in the centre of the villages, which could not be altered during the process due to the hut being part of the experiment. This resulted in 12 out of 68 log files having to be excluded from evaluation due to inference from bystanders or tips given by the indigenous research assistants. Despite being informed repeatedly to not interfere, it seemed important to them to see their community members succeed.

During the following research trip, two strategies were tested: immersion and separation. The first approach, realised in the Treasure Hunt experiment, was to entirely omit the 'classroom situation' and instead turn the experiment into a game. In this, the participants were encouraged to build groups and collaborate while performing the tasks. Importantly, there was no researcher or research assistant present during the runs. Instead, the tablet running the Treasure Hunt app logged the groups' GPS locations as well as all user interaction. A considerable limitation of this approach was that the logs do not give any indication whether the device was in active use at a given moment in time. Furthermore, despite 'screen pinning' being enabled, two of the groups managed to exit the app during their Treasure Hunt runs and did not know how to restart it. With no researcher present to assist, both groups had to be excluded from the evaluations.

After the immersive Treasure Hunt, participants took part in another structured and supervised experiment to edit locations and features on a digital map. The approach was slightly improved compared to the Image Tapper experiment, with the research assistant separating the participant from the group, sitting them down at a bench further away from the rest of the people. This way people could not interfere and the research assistant could more calmly explain the procedure. Additionally, participants were already familiar with the tablet from the previous Treasure Hunt experiment, which seemed to take away some of their fear of breaking the device.

Unsurprisingly, participants seemed happier about carrying out the Treasure Hunt experiment compared to the structured one. This was later confirmed by a group of women in an informal conversation facilitated by the translators. Finding the treasures gave the participants a sense of achievement, however, during the assisted experiment each interaction was logged but the participants were intentionally never told whether their choice was correct in order to avoid disappointment or individual comparisons. On the downside, this meant they did not receive any positive feedback about their performance either.

Computer logging, which belongs to the category of empirical observation methods in usability engineering (see section 4.1.1), was adapted for all experiments carried out in this research. In order to judge the participants' performance and to analyse the types of interaction used during the unsupervised Treasure Hunt experiment, analysis methods based on time synchronisation of location and user interaction were developed. Despite the uncertainties connected with relying exclusively on computer logging, insights could be gained that were not accessible through direct observation or facilitated interviews.

A UCD cycle was realised in parts, with adaptations made to common testing methods. Instead of insisting on specific procedures, the philosophy applied in AR was followed, where the participant is more important than the protocol. To carry out the research for this thesis, three field trips were realised with two iterations of map reading experiments. The idea of the UCD design cycle 'fail frequently, fail fast' (see section 4.1) with many iterations of throwaway prototypes remains a challenge in the context of working with remote communities, due to costs and the commitment of institutional partners, discussed in the next section.

### 8.2.3 Institutional Collaboration

As outlined in section 5.1, ExCiteS partnered up with two NGOs who expressed an interest in using the Sapelli collector to improve their monitoring practices: Resource Extraction Monitoring (REM) and Forests Monitor. Both institutions, however, ended the collaboration in the first year of ExCiteS' involvement. Furthermore, during the search for possible partners, the national park Odzala, in the west of the Republic of the Congo, was a prospective partner. The cooperation, however, fell through after a change in management did not see the protection of forest people's way of life as a priority.

A collaboration with the logging company CIB made it possible to travel to the Republic of the Congo. The challenges a remote environment (see section 2.3) poses, however, place a research team in a vulnerable position as they are dependent on institutional commitment for legal, logistical and organisational matters. CIB's support defined the success of the project as they were the ones who arranged invitation letters required to obtain visas, provided transport, accommodation and the research assistants. The cooperation meant mutually suitable travel dates had to be arranged, requiring leniency on the project requirements in order to accommodate to the availability of CIB staff.

A visa is required in order to conduct academic research in the Republic of the Congo. This is granted based on a written permission provided by the relevant Ministry in Brazzaville, before entering the country, as well as an accommodation certificate. The logging company agreed to arrange the documents for the researchers but as no concrete processing times were defined, there were periods of uncertainty regarding travel dates. In addition, weather conditions such as seasonal floods in the country restricted the time of travel.

Once in the field, the researchers were assisted by CIB's social team. The social team consists of indigenous people who in the role of communicators act as a point of contact between the company's management and the forest people. Under the agreement between ExCiteS and CIB, the social team assisted the researchers' work in the field as facilitators, translators and research assistants. The team spoke the local Mbendjele language as well as French, thus mediating between the research team and the pygmies. They took care of logistical concerns such as organising necessary transport to access the communities in the rainforest. They also opened up the trust of the communities towards the researchers, making it possible to find participants and conduct mapping experiments.

The communicators took on this task in addition to their general daily commitments. This often meant research delays while the communicators tended to their own priorities. In a project where there is limited time available in the field, uncertainty is challenging and requires flexibility from the research team.

### 8.2.4 Importance of Interdisciplinary Collaboration and Skills

The Committee on Facilitating Interdisciplinary Research, set up by US National Academies of Sciences, Engineering, and Medicine names four main factors driving interdisciplinary research (IDR): the inherent complexity of nature and society, the desire to explore problems and questions that are not confined to a single discipline, the need to solve societal problems, and the power of new technologies (NAP, 2005).

Driven by similar desires, the ExCiteS Intelligent Maps project explores social empowerment in a remote environment employing digital technology, thus it calls for an IDR approach bringing together the expertise of researchers from the fields of anthropology, computer science as well as geographical information science (see table 2.1). Rather than adhering to the methods of just one of the three disciplines, their combination is more suitable given the complexity of the research context as described in chapter 2.

Interdisciplinary thinking is an integral feature of HCI research as well (Thimbleby, 2004). Ethnography in particular is often used for better understanding of a product's context (Vertesi et al., 2011; Williams and Irani, 2010). In the case of Intelligent Maps, social and cultural anthropologists provided insight into how to best collaborate with local communities while also providing insight to the locals on how to best approach the research, thus legitimising the project for stakeholders on either side. The work of anthropologist Dr. Jerome Lewis and Gill Conquest in particular paved way for the execution and evaluation of the field experiments required for this research. As outlined in chapter 2, Lewis made collaboration with CIB possible. Conquest created the appropriate context for the research trips, engaging the local communities and followed the progress of the experiments for the first part of the trip, as one aspect of her research concerns how the ExCiteS software developers design for non-literate communities.

The integration of information, data, techniques, tools, perspectives, concepts, and/or theories from multiple disciplines advances fundamental understanding (NAP, 2005), however, interdisciplinarity also poses challenges when the disciplines involved have different priorities in mind within the same project. Whereas computer science and GISc tend to follow strict quantitative protocols and employ usability studies, anthropology defends the perspective of a subjective researcher (Spiro, 1996).

As a result of this polarity, both sides had concerns to address. During the initial field study, discussions on the scope of the project and the FPIC process with participants, (a priority of the anthropology discipline), stretched out and caused complications for the technical team, who were required to carry out time-sensitive evaluations with limited time available in the field. IDR projects thus require effective communicators who are able to acknowledge the priorities of all the disciplines involved and find the necessary compromises. Due to the disparate backgrounds in IDR, it takes time to build consensus.

This requirement applied throughout the entire duration of the project as the researchers were co-dependent on each other with one or the other party often having to wait for the results of others in order to carry on with their work. For this reason, managing expectations as well as escalating issues as they arouse was essential for the smooth running of the project and consensus needed to be repeatedly established. In the context of the ExCiteS collaboration, the team needed to readjust what was expected from the different disciplines in terms of delivery. At times, the social scientists were impatient to introduce new software to local communities that was not yet developed by the technical team. On other occasions, the computer scientists had the technology ready to be tested but the opportunity had not yet been established by the anthropologists. Both sides of the IDR team had to acknowledge that developing brand new software requires time and resources and so does establishing local partnerships and opportunities.

A stable IDR team, however, does not guarantee a successful collaboration. The success of IDR groups depends on institutional commitment as well (NAP, 2005), which introduces more factors of uncertainty, as discussed in the previous section. Sapelli is a collaborative output, therefore the presence of the IDR team was required on the ground for software related HCI research as well as icon design user studies. The fact that the project offered the partner institution the ready-to-use software Sapelli, along with a team to deploy it free-of-cost, made collaboration more appealing to CIB. Consequently, in return for the free technology and IT support, the company was permissive with the team to use the opportunity to conduct their own field studies on their logging concession regarding modes of data collection (Vitos), knowledge creation (Conquest), and, the topic of this thesis, map understanding.

Given the complexity of the project, in addition to the interdisciplinarity of the group of researchers as a whole, the interdisciplinarity of individual members of the team was also of significance. In the case of this research, a sound background in GISc, as well as geography and computer science was imperative. As Lippincott and Dosemagen (2015) put it, geographers and 'people-centric mappers' are technically-oriented social scientists. This diverse background was beneficial to the implementation of this project, as it involved the development of appropriate methodologies to conduct empirical map reading experiments with communities as well as developing all the necessary bespoke tools to conduct these experiments and answer the Research Questions. Thus, knowledge in multiple disciplines was necessary as, in addition to devising the methodology for the research, all its technical requirements were dealt with by the researcher first hand. Bespoke Python scripts were written to develop the flight planner, FPV2KML converter as well as the Voronoi diagrams. A Python script was also used to test map understanding with the development of a bespoke coordinate viewer and to make optimal route calculations. Three Java based Android apps were developed for testing with the local non-literate communities: the Image Tapper, Treasure Hunt and Got it Right. The possibility to develop and modify all experiment apps as well as custom scripts for preparation and evaluation has created opportunities that would not have been possible through the use of existing tools and methodologies.

## 8.3 Future Work and Recommendations

The research presented in this thesis is the first part of the project Intelligent Maps, described in section 2.4, concerning data visualisation. For the continuation of this research effort to fully implement the vision, the ExCiteS research group was awarded with €2.5m. The funding will allow the group to build on the development of accessible PGIS tools.

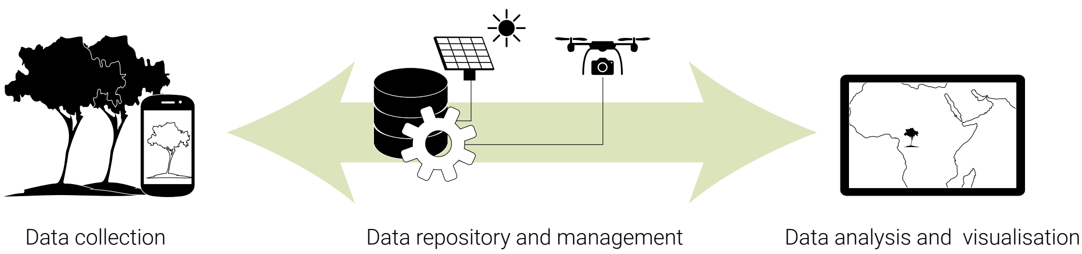



***Figure 8.2*** *Intelligent Maps*

Figure 8.2 shows the schematic implementation of 'Intelligent Maps' with data flows from various data collection applications to a repository including imagery from UAVs. The information is displayed on a tablet computer that can be used to view and update the data. Research effort is necessary to streamline image processing on a small rugged server that can be deployed in remote locations with limited energy supply.

The focus of this research was on the the base map itself as well as basic GIS concepts like zoom and pan interaction and thematic overlays. The theoretical lack of suitability of visual realism for task performance (see section 3.2.2) could not be assessed in this research, due to the lack of availability of less visually real maps. Non-photorealistic maps could be derived from aerial maps produced in this research and compared for effectiveness. Further research needs to be carried out exploring culturally appropriate symbology and interaction methods. A further challenge lies in the inclusion of area data alongside point data. Furthermore, usability experiments should be carried out for methods of aggregation and generalisation of displayed information and, finally, data analysis results in the form of graphs and other graphic displays should be tested for understanding.

The research indicated that participants showed positive reactions and high success rates when interacting with tangible user interfaces (e.g. NFC cards). More research is required to confirm assumptions suggesting that a stylus pen may help to overcome some of the participants reluctance to touch the screen.

Together with ExCiteS member and anthropologist Gillian Conquest, parts of the experiment apps used in this research have been combined to create the 'Sapelli Viewer' app (see figure 8.3) – a prototype visualising data points captured with Sapelli. The prototype was shown to indigenous youth groups in Central African Republic (CAR) during a resource mapping exercise. Systematic research is necessary to evaluate whether direct visual feedback improves understanding of the mapping activity.

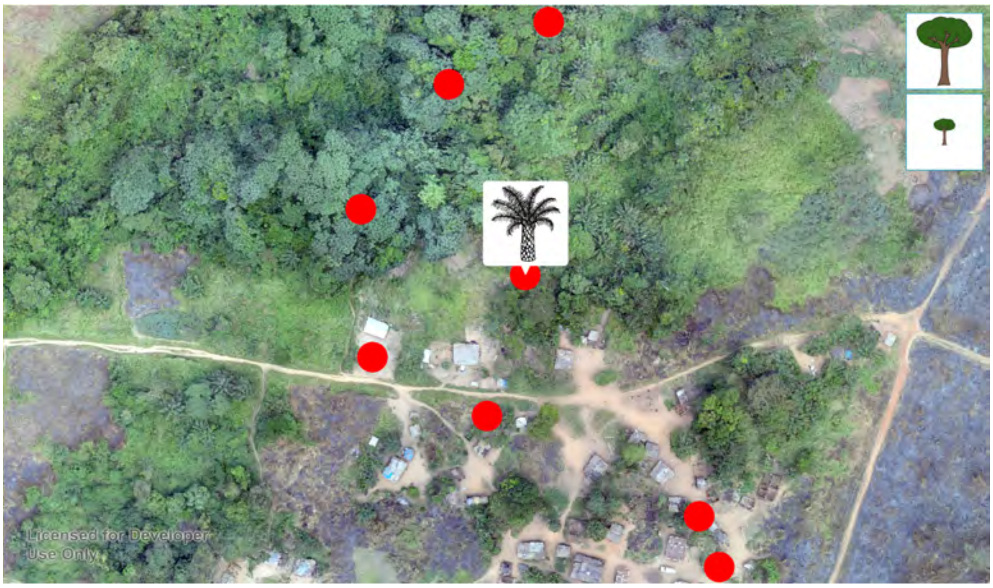



***Figure 8.3*** *Sapelli Viewer*

Future work should make use of the unsupervised research methods but include more sensors. Through the recording of accelerometer measurements as well as video, it can be analysed when participants actually consult the device, how they collaborate within the group and how they go about problem solving.

Experiment participants should have the option to explore devices on their own and have enough time to overcome potential reservations in regards to interacting with technology. Providing a practical task to solve, such as a Treasure Hunt, facilitates that phase of exploration.

Importantly, the communal nature of local culture should be taken into consideration when designing user experiments. In this research, the best results were achieved when people were either carrying out a specified task in a community or in isolation from the community.

Participants should be made to feel at ease during the execution of experiments. In order to achieve an environment free of stress, researchers must invest time in gaining the trust of local communities. If, however, language barriers pose obstacles to participant engagement, it helps to train an intermediary with the language skills to act on behalf of the researchers, as they have quicker and more meaningful access to the community. In this research, good results were achieved by building trust with an intermediary, making sure that he really understands the procedure before interacting with the communities in their local language.

## 8.4 Summary and Outlook

The chapter discussed the findings and contributions in aerial map creation and aerial map understanding. It is important to point out that all participant samples were self selected and limited in numbers. It can be said with fair confidence that the map reading experiments showed that high resolution maps, devoid of textual elements and complex user interaction designs, could be understood by people who have never seen a map before. Thus there is potential for GIS technology to be developed with people in mind and maps can cater for non-literate forest people.

The chapter reflected on the need to modify traditional HCI test protocols when moving such experiments from controlled lab situations into the rainforest due to the cultural differences, communication barriers as well as time constraints. Time was a pressing matter during the field trips due to the constraint imposed by institutional collaboration, which on the other hand, also provided freedom for an interdisciplinary team to pursue their individual studies in addition to bringing their skills together for the success of the Intelligent Maps project.

The results of the experiments carried out for this research show that non-literate, indigenous people who have never been exposed to maps or technology were able to utilise digital maps, even in unsupervised situations, in order to accomplish tasks. This has the potential of changing public attitudes towards the abilities of marginalised, non-expert groups. Visiting these communities has revealed that people are very willing to share their insights about the sensitive environment that they live in and the threats it is facing, but they have no means to communicate. Forest inhabitants have a natural interest in reporting wildlife crime, such as illegal logging or wildlife poaching, which can lead to efficient law enforcement in vast rainforest areas that were previously impossible to control. Hunter-gatherers are often put in the same category with commercial poachers ignoring the fact that subsistence hunters have the highest interest in forest and livestock health. Nonetheless, indigenous peoples who have inhabited forests for thousands of years are often banned from conservation zones such as national parks. An ongoing project between ZSL and ExCiteS aims to provide a way for forest people to report illegal wildlife crime using the Sapelli collector (see section 2.4.2). Within the first two months, indigenous people have, amongst other incidents, reported the locations of 372 found shotgun cartridges. A problem this project is facing at the moment is not the lack of reports by indigenous people, but that local officers from the Ministry of Forestry and Wildlife do not have accurate maps to find locations of reported incidents and follow up on those. High resolution offline maps as generated in this thesis can be of great support in such situations.

The systematic process of map generation proposed in this research can furthermore be used by other practitioners that require timely updated local maps, such as disaster response teams. The humanitarian mapping charity MapAction report that so far they have not made use of UAV imagery, due to the following reasons: "We cannot necessarily download large volumes of data due to thin or interrupted internet connections. We have very little time to stitch lots of imagery together, process that raw imagery, or analyse the bands of data into something meaningful. And we are bombarded by multiple requests to process data for a range of relief managers in a rapidly evolving situation, so we work under acute time and technological constraints" (Mills, 2018).

Within academia, methodologies developed for empirical experiments with people across cultures and language barriers can be adapted for others studying use of technology across language and cultural barriers. This research has paved the way for the development of a socially and culturally accessible GIS interface and underlying algorithms and is part of a bigger vision to create analysis and visualisation tools that will allow any community – regardless of literacy – to monitor and manage their environment in a way that fits with local culture and social practices. Taking this research further has the potential of enabling people to communicate issues such as reporting environmental and social crime and injustice. With appropriate procedures in place, this can enable full co-production of knowledge between indigenous groups and scientists in some of the most critical environments on Earth. Communities can be provided with tools to support them to combine their local environmental knowledge with scientific analysis to improve environmental management. The greatest impact for society can be gained where participants use scientific tools to improve their environment locally and share the knowledge globally. In addition to community empowerment, this gives new insights for scientists and the public alike that would otherwise be inaccessible.

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# Appendix

## A.1 Principles of Usability

Usability means that the system must be:

- useful – achieves the desired goal;
- usable – does it effortlessly and efficiently, without the risk of making errors; and
- used – makes people want to use it, is attractive, enjoyable, engaging (Dix, 2004).

There is no general agreement on how to ensure usability but several authors have proposed measures of usability (Nielsen, 1993; ISO 9241-11, 1998; Shneiderman and Plaisant, 2004; Dix, 2004). Despite some variations in the details, there emerges a consensus on the main ideas (table A.1).

***Table A.1*** *Measures of usability (Van Welie et al., 1999)*

| ISO 9241-11 | Nielsen | Shneiderman |
|---|---|---|
| Efficiency | Efficiency | Speed of performance |
| | Learnability | Time to learn |
| Effectiveness | Memorability | Retention over time |
| | Errors | Rate of errors by users |
| Satisfaction | Satisfaction | Subjective satisfaction |

The definition ISO 9241-11 (1998) identifies usability measures as *Efficiency* (resources expended in relation to the accuracy and completeness with which users achieve goals), *Effectiveness* (accuracy and completeness with which users achieve specified goals) and *Satisfaction* (freedom from discomfort, and positive attitudes towards the use of the product). Nielsen's usability attributes are more specific than the rather theoretical ISO definition. He adds *Learnability* (the system should be easy to learn) and subdivides *Effectiveness* into *Memorability* (the system should be easy to remember) and *Errors* (the system should have a low error rate). The definition following Shneiderman differs in terminology, but is essentially identical to Nielsen's definition.

A rather different definition is given by Dix (2004) who defines three main concepts that support usability, further subdivided into the factors that influence the respective concept (Table A.2). *Learnability* is the ease with which novice users are able to effectively and successfully interact with the system, *Flexibility* indicates the multiplicity of ways users interact with the system, and *Robustness* is the level of support provided for the users to achieve and assess their goals.

***Table A.2*** *Principles to support usability (Dix, 2004)*

| Learnability | Flexibility | Robustness |
|---|---|---|
| Predictability | Dialog initiative | Observability |
| Synthesizability | Multi-Threading | Recoverability |
| Familiarity | Task Migratability | Responsiveness |
| Generalizability | Substitutivity | Task conformance |
| Consistency | Customizability | |

Where Nielson and the ISO standard provide a generic framework of usability, Dix focuses on precise elements that influence it, which are described in detail in Dix (2004). This tangibility offers great potential for designers to implement the respective concepts. However, it does not incorporate the efficiency and error rate aspects, which the other authors have pointed out to be clear indicators of usability (Van Welie et al., 1999).

## A.2 User-Centred Design

Before the emergence of HCI it was commonly believed by technologists that users are able to adapt to whatever technologists build. System development was purely technology-driven (Oviatt, 2006). This way of thinking created problems, particularly in the 1970s and 1980s, when computers were introduced widely in offices and non-specialists had to learn how to use them in order to accomplish their tasks more efficiently (Haklay and Nivala, 2010). Don Norman, a pioneer in HCI research, discovered that bad system design, as well as non-technical design, often lead to frustration in the user. If users cannot figure out how to operate a device, they usually blame themselves. Often they feel that they are not clever enough to figure out the correct usage. Norman promoted the idea that the real problem is not human incompetence, but bad design that often provokes performance errors. This problem can only be overcome if the design focus lies on the potential users rather than on the resulting product. The now well-established term User-Centred Design (also Human-Centred Design) was born when his co-authored book *User-Centred System Design: New Perspectives on Human-Computer Interaction* (Norman and Draper, 1986) was published. He further pushed that idea in his book *The Psychology of Everyday Things*, (Norman, 1988), later *The Design of Everyday Things* which became a best-seller with its third edition published in December 2013 (Norman, 2013). Nowadays the UCD approach is widely recognised for system development (Abras et al., 2004; Norman, 2005). ISO 9241-210 (2010) defines UCD as: "An approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques". The core method of UCD is the iterative design cycle (see figure A.1). Its four activities are repeated with each iteration showing improvements towards the desired solution. The individual steps are explained in the remainder of this section.

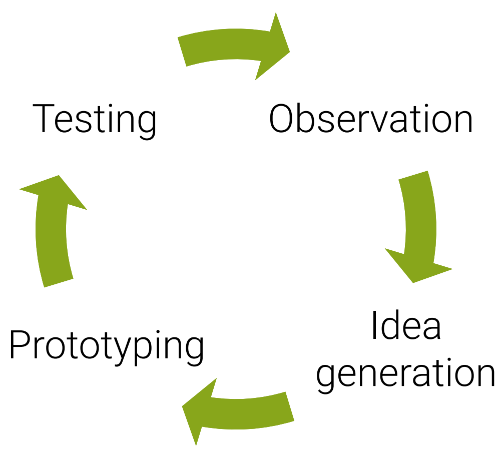


***Figure A.1*** *Iterative cycle of User-Centred Design (Norman, 2013)*

The observation phase breaks from the positivist approach to research, where the scientist remains detached from the participants. Instead, the user is the focus of attention. The principle of the observation stage is to observe the activities of potential users and identify their motives and needs. For this it is crucial to observe the users in their natural environment, i.e. the environment in which the product or service will be used. Solutions being developed in isolation from the real situation have often led to ’unusable’ systems in the past. The method of observing potential users in their native environment, called applied ethnography, is adapted from the field of anthropology, which leans heavily on the technique of participant observation. Norman (2013) points out the importance of studying the exact population. He warns against remaining at home and relying on stories told by visitors. In order to identify the right problem and consequently find an appropriate solution to that problem, a deep understanding of the target population, including their activities, experience and cultural issues, is required. After determining the requirements, the designer’s next step is to find potential solutions. Here it is critical to be creative and it is important to not prematurely dismiss ideas. There are multiple ways of generating ideas. Many of these methods are forms of the superior technique of brainstorming. In the prototyping phase the possible solutions identified in the previous stage are put into practice. It is not necessary to develop fully functioning solutions yet. Often it is useful to create quick mock-ups in order to identify previously undiscovered problems.

Once a prototype is ready for testing, it is key to identify a small group of people that closely relate to the target audience, in order to trial the prototype under authentic conditions. It is useful to have two people using a prototype together, exchanging their thoughts while doing so. This way, pairs are likely to discuss their ideas, hypotheses and frustrations openly and naturally. The Thinking Aloud method is further discussed in section 4.1.1. Research conducted by Virzi (1992), Lewis (1994) and Nielsen (2000) suggest that five participants being studied individually will yield 80% of the usability findings. If a bigger sample size is desired it is suggested to use the results of the first five participants, and iterate through the test-design cycle until the desired number of participants is reached. This gives multiple iterations of refinement and enhancement rather than just one.

According to David Kelly, Stanford professor and co-founder of the design company IDEO, the best approach for a successful design is to "fail frequently, fail fast" (Norman, 2013: p.229). The iterative design cycle provides an opportunity to act on the failures of the previous iteration. The first and most challenging part is to get the requirements right, which is the prerequisite for finding an appropriate solution to the initial problem. Subsequently the test results are used to determine which parts of the design work, and which do not. The iterative cycle is repeated until a satisfying result is achieved. After the first few iterations, it is time to start converging upon a solution. The various prototypes can be collapsed into one.

Despite the high acceptance of UCD, Norman (2005, 2006) himself criticises its lack of flexibility. He further concludes that tailoring systems to specific individuals' needs might make them less usable for others. There are many examples of successful design that are used by a very wide range of people, such as a car or a musical instrument. None of these are intuitive and using them requires training. Norman (2013) argues that, despite cultural differences, activities across the world are often similar. Therefore, good design will seamlessly package together the individual tasks that are required to perform an activity. By understanding the activity, the device will be understood. This approach is called Activity-Centred Design (ACD), and has its roots in Activity Theory (Williams, 2009). According to Saffer (2010), activities are defined as a set of decisions and actions that are executed to achieve a higher-level goal. The main difference from UCD is that users are observed in order to study their interaction with the system, rather than their goals. Norman (2006) uses the example of hammer and nails to illustrate his point. UCD would suggest categorising nails with nails and hammers with hammers because that is the logical thing to do. Although this way of organising is well-suited for retrieval, it does not directly support the activity. Following the ACD approach means keeping the hammer with the nails, since they will be used together. The need to get both of the items from different places adds unnecessary complexity to the activity. This principle can easily be projected onto technological systems. For instance, after taking a photo with a mobile phone, the user should have immediate access to the send or delete options. This step is part of the activity 'take photo' and therefore it should not be necessary to go through the settings menu to do so, even though it might be a logical place to put this option (Norman, 2006).

## A.3 Travelled Distance Calculation

The TSP lengths are the sum or linestrings that make up the shortest route, imported from PostGIS (lines 5-8). The travelled distances are the lengths of the linestrings connecting the recorded GPS points in chronological order, per group (lines 10-14). To facilitate distance calculation, the coordinates were transformed into a UTM 33 coordinate system (line 12). The implementation of this query in PostgreSQL/PostGIS can be found in Appendix A.5

```
1  SELECT
2    groupid,
3    travelled_length / tsp_length AS travelled2tsp
4   FROM
5     SELECT
6      group_no,
7      SUM (LENGTH (TSP LINESTRINGS) ) AS tsp_length
8     FROM tsp
9   JOIN
10    SELECT
11      groupid,
12      LENGTH (TRANSFORM TO UTM (MAKE LINE (GPS POINTS)))
13      AS travelled_length
14    FROM gps_logs
15  ON tsp.groupno = gps_logs.groupid;
```

## A.4 Off-Track Route Calculation

To ensure readability and maintainability the calculation of detours is carried out in two steps. First a view is created that takes the *GPS_logs* table and appends an additional column called 'off-track'. The value is set to *TRUE* if the distance between the GPS location and the aimed for treasure is bigger than the previous GPS to treasure, given that the group id is the same (lines 8-10). In the second step clusters are created, grouping consecutive *off-track* values (line 18) and consequently all clusters where the *off-track* flag is *false* are filtered out (line 20). The remaining clusters are finally connected to linestrings (line 15). The implementation of this query in PostgreSQL/PostGIS can be found in Appendix A.5.

```
1  CREATE VIEW directional_gps_log AS
2    SELECT
3      gps_logs.*,
4      (gps_logs.id IN (
5        SELECT id
6        FROM gps_logs
7        WHERE
8          DISTANCE gps_logs.geom TO treasure.geom >
9          DISTANCE PREVIOUS gps_logs.geom TO treasure.geom AND
10         groupid = PREVIOUS groupid)) AS off_track
11   FROM gps_logs;
12 
13 SELECT
14   groupid, Min(time), Max(time),
15   MAKE LINE FROM AS cluster
16 FROM (SELECT
17         groupid, time,
18         CONSECUTIVE OFFTRACK VALUES AS cluster
19       FROM directional_gps_log
20       WHERE off_track IS TRUE)
21 GROUP BY groupid, cluster;
```

## A.5 Digital Appendix

Software

- Flight planner
- FPV2KML
- Image Tapper App
- Coordinate viewer
- Voronoi generator
- Treasure Hunt App
- Route calculator
- Got it Right App
- SQL scripts

Treasure Hunt videos (also under http://bit.ly/treasurehunt-videos)

| | Sembola | Matoto |
|---|---|---|
| Female | f2, f3, f9, f10, f11 | f5, f6, f7 |
| Male | m2, m9, m10, m11 | m4, m5, m6, m8 |

Orthophoto maps

- Sembola
- Matoto